American Journal of Modern Physics
2025, Vol. 14, No. 2, pp. 80-90
https://doi.org/10.11648/j.ajmp.20251402.14

Research Article

Mechanism of Salt's Surface Crystallization at Djègbadji Salt Marshes, Benin (West Africa)

Armel Vitouley[1], Guy Hervé Houngué[1,*], Gabin Koto N'gobi[1], Julien Adounkpè[2], Waliou Amoussa Hounkpatin[2], Clément Ahouannou[3], Basile Kounouhéwa[1]

[1]Department of Physics, University of Abomey-Calavi, Abomey-Calavi, Benin

[2]Faculty of Agronomic Sciences, University of Abomey-Calavi, Abomey-Calavi, Benin

[3]Polytechnic School of Abomey-Calavi, University of Abomey-Calavi, Abomey-Calavi, Benin

Abstract

Salt production, a key component of the local economy, relies on complex natural processes, particularly capillary rise and surface crystallization. In Djègbadji, Republic of Benin, salt is produced by boiling brine, which is obtained through the leaching of salt-laden soils. Although this traditional method has been practiced for generations, it is highly dependent on the hydrodynamic properties of the environment and the specific characteristics of hydromorphic soils, which influence the movement of water and salts. In these salt marshes, the interactions between water, soil, and air play a crucial role in salt formation and concentration. However, a detailed understanding of the underlying mechanisms remains a scientific challenge. This study employs theoretical and experimental approaches to analyze these phenomena. The one-dimensional Terzaghi equation is used to model the interactions between soil parameters and capillary forces, while the Navier-Stokes equation is applied to examine salt crystallization. These tools provide a deeper insight into the physical dynamics governing this unique ecosystem, enabling a better understanding of water and salt migration. By integrating numerical modeling, this research aims for a sustainable optimization of salt production techniques. The expected results will contribute to better resource management, while offering perspectives for improving local salt production and its adaptation to current environmental challenges.

Keywords

Saliculture, Hydrodynamics, Crystallization, Capillarity, Numerical Modeling, Djègbadji, Salt Marshes

1. Introduction

Salt production is an income-generating activity for salt growers [1-3]. To produce salt, three (3) methods are traditionally used: (i) rock salt extraction [4-7], (ii) solar salt production or solar evaporation [8-12] and (iii) salt production by cooking [12-14]. At the Djègbadji site in Benin Republic, salt is produced by cooking the brine obtained through leaching the salty soil scraped from the salt marsh floor [2, 13]. The crystallization of salt is a phenomenon that occurs during the favorable and greatest salt-growing periods, from November to March [15]. The soil of the Djègbadji salt marshes

*Corresponding author: hguyherv@gmail.com (Guy Hervé Houngué)

Received: 4 February 2025; **Accepted:** 19 February 2025; **Published:** 14 April 2025

is a salty and silty soil considered to be hydromorphic [16]. The phenomenon that leads to salting the Djègbadji salt marsh soil surface can be declined in two processes: (a) the capillary ascent of brackish water from a shallow underground water reached around 50 - 60 cm under the surface [16, 17] and (b) the crystallization of salt at the surface [17]. In porous locations, underground movement of water can be governed by hydraulic gradients [18-20]. But osmotic gradients [21, 22], temperature gradients [23-26], electrical gradients [27], chemical gradients [20], gravity and matrix pressure gradients and even vapor pressure (evapotranspiration) [28], are all forces that can also induce groundwater flow in these environments [29]. In the particular case of capillary ascent of water in the ground, fluid movement is governed by hydraulic head gradients [18]. From the point of view of static and dynamic properties, the movement of a liquid in a capillary tube presents some interesting characteristics and, it is therefore an ideal setting for the application of surface tension effects (contact angle, notion of wettability and adhesion of liquids to solids) as well as some of the fundamental concepts of fluid mechanics [30-33]. In the past decades, several authors have focused on the phenomenon of fluid ascent by capillary action and salt crystallization [32-40]. In particular, the liquid column inside a tube was described by Menon and Agrawal [34] as a mechanical system with variable mass. Thanks to Newton's equation, the phenomenon was understood under simplifying assumptions leading to theoretical solutions. Similarly, in 1996, Duarte et al [32] described the motion of viscous fluid in a capillary tube, using the fundamental laws of hydrodynamics and the Navier-Stokes equations. In 2004, Lu and Likos [18] developed a rigorous closed-form analytical solution for the analysis of capillary rise rates in soils. This new solution, compared with Terzaghi's classical one and with a series of experimental data from open-tube capillary rise tests, was found to provide more realistic and practical predictions of the capillary rise rate in unsaturated soils. As for the crystallization phenomenon, in 2022, the shape and size distribution of salt crystals induced by the crystallization mechanism were studied by Alireza et al, [38] and, their results opened avenues for controlling the size and shape of crystals and patterns formed in a complex gel matrix. For Mancigotti and Hamilton [39], the constraints exerted by crystallization on the porous host, the growth rate of mirabilite crystals as well as the degree of supersaturation of the solution with respect to mirabilite at the initiation temperature were studied. They observed that mirabilite crystallization is exothermic and then, they related the heat produced to the quantity of crystals formed. They also discovered that mirabilite-ice eutectic point occurs at -3℃ and results in complete solidification of the remaining liquid phase accompanied by damage. The problem of crystallization is addressed by Veran-Tissoires et al, [40], with a view to understand the choice of a location of crystallization on the surface of a porous site. For Shah et al, (2011) [41], soil salinization would be the result caused by upward capillary flow of poor-quality groundwater; for Norouzi Rad and Shokri (2012) [42], salt distribution and precipitation depend significantly on salinity as the concentration gradient generates flow in and around the column of highly saline water. According to Nachshon et al (2011) [43], salt dissolved in groundwater is transported by capillary action in arid zones, eventually precipitating and accumulating near the soil surface in the vadose zone. To our knowledge, no work has yet been carried out on the capillary rise of water in the soil and the crystallization of salt at the soil surface in Benin. In this work, the capillary rise of water in the soil of the Djègbadji salt marsh, the influence of different soil parameters (hydraulic conductivity at soil saturation (ks), soil porosity (n), liquid-solid contact angle (i) and rate of decrease in hydraulic conductivity (a) on this phenomenon and the crystallization of salt at the soil surface were analyzed using the fundamental laws of hydrodynamics and the Navier-Stokes equation. The study explains the physical processes taking place during the capillary rise at the Djègbadji salt marsh. The next sections of the paper present respectively, the material and the method, the obtained results and the concluding remarks

2. Materials and Methods

2.1. Study Area

Djègbadji is a district within the municipality of Ouidah, located in the Southwest of Benin, a country in West Africa, at coordinates 6°17'54" to 6°20'48" North latitude and 1°58'36" to 2°7'39" East longitude [44]. This region has a climate characterized as subequatorial bimodal. Throughout the year, it experiences four distinct seasons: a major rainy season from April to mid-July, a minor rainy season covering the period from mid-August to mid-October, a major dry season from mid-October to March, and finally a minor dry season observed from mid-July to mid-August [15, 45, 46]. According to research conducted by Boko in 1988 [47], precipitation during the major season varied between 40 and 65%, while that during the minor season ranged from 18 to 30%. Furthermore, in 2018, statistical data provided by ASECNA indicates that the annual cumulative precipitation ranges between 950 and 1300 mm [46]. Regarding the winds, an average speed of about 4 $m.s^{-1}$ is recorded with a predominant direction oriented towards the Southwest [17, 46]. The average temperature is around 28.04 $°C$; the average humidity reaches 81.04 %; the average radiation amounts to about 50.21 $kWh.m^{-2}$; the average insolation is estimated at around 4.98 $kWh.m^{-2}$ [15] while the average net radiation is estimated at around 401.35 $W.m^{-2}$ 401.35 $W.m^{-2}$. The local topography is marked by the presence of the coastal lagoon also known as Djessin lagoon, which houses salt marshes and swamps. Endowed with a soil classified as silty and hydromorphic [16], this region is home to various plant species such as mangroves and coconut trees.

2.2. Capillary Rise Phenomenon

The figure 1 below illustrates the capillary rise process in soil. It shows the soil profile delineated by three distinct zones. The First zone (zone 1) is below the water table. The pore water pressure is considered positive in that zone. The second zone is located under the air inlet head (h_a) but above the water table. The pore water pressure is negative to atmospheric pressure. Finally, the third zone is unsaturated and is above the air intake head, where the capillary water rises like a series of fingers connected or disconnected at a maximum height (h_c). The capillary rise's water phenomenon in unsaturated soil is therefore described as the movement of pore water from a lower to a higher level. This phenomenon of water circulation occurs due to the hydraulic head gradient acting across the interface between pore air and curved pore water [18].

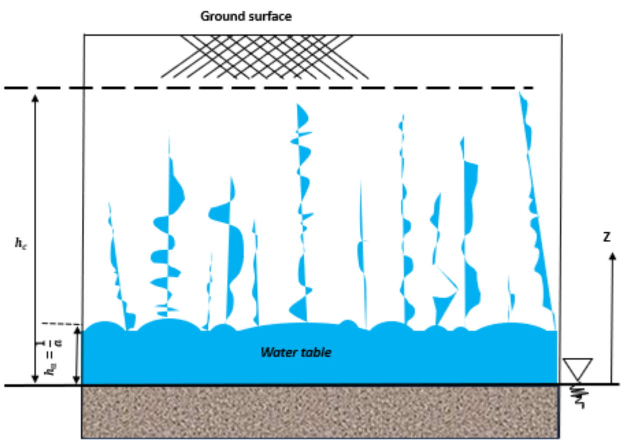

Figure 1. *Illustration of capillary rise in soil, inspired by [18].*

To analyze capillary rise's phenomenon, Terzaghi equation governing the one-dimensional motion of capillary rise of water in homogeneous, rigid porous media (soil) with varying degrees of saturation (equation 1) [18, 48], is used:

$$\frac{dz}{dt} = \frac{k_s}{n} \exp(-az) \left(\frac{h_c - z}{z}\right) \quad (1)$$

In this equation, the maximum height of capillary rise (h_c), is given by equation (2) [49]:

$$h_c = \frac{n\gamma}{\sqrt{2\eta \rho_w g k_s}} \cos(i) + (1-n) h_a \quad (2)$$

where k_s, is the hydraulic conductivity at saturation of the soil; n, the soil porosity; i, the liquid-solid contact angle; ρ_w, the density of water; g, the earth's gravity; η, the kinematic viscosity of water; γ, the surface tension and h_a, the air entry height or height of the saturated part of the capillary fringe given by relation (3) [18]:

$$h_a = \frac{1}{a} \quad (3)$$

Physical parameters used in this work come from the work of Duarte et al [32]. These values correspond to those of water considered at 30°C. They include parameters such as: gravity intensity $g = 980\ cm.s^{-2}$; surface tension $\gamma = 70\ dyn.cm^{-1}$; water density $\rho = 1g.cm^{-3}$ and kinematic viscosity $\eta = 8{,}31.10^{-3} Pl$. The constant c was set at $c = 20$.

Data from soil parameters such as hydraulic conductivity at soil saturation (k_s), rate of decrease of hydraulic conductivity (a) and soil porosity (n) were used [50, 51].

2.3. Crystallization

To better understand how salt crystallizes on the soil surface of the Djègbadji salt marshes, we resorted to the Navier Stokes equation given in relation (4).

$$\rho \left[\frac{\partial u}{\partial t} + (u.\nabla)u\right] - \mu \Delta u = -\nabla \vec{p} + \rho \vec{g} + \frac{1}{3}\mu \nabla(\nabla.u) \quad (4)$$

with ρ, density; μ, dynamic viscosity; $\vec{p}$, pressure field and $\vec{g}$ gravitational force.

By applying the law of conservation of mass and considering that water is incompressible everywhere and at all times, i.e. [52]:

$$\nabla.u = 0 \quad (5)$$

The Navier Stokes equation given by relation (2) reduces to [32, 52-54]:

$$\rho \left[\frac{\partial u}{\partial t} + (u.\nabla)u\right] - \mu \Delta u = -\nabla \vec{p} + \rho \vec{g} \quad (6)$$

Since water subject to evapotranspiration must evaporate, we assume that water on the ground surface is not under the influence of turbulent acceleration or external forces (pressure field and gravitational forces). Under these conditions, we have: $(u.\nabla)u = \vec{0}$, $\nabla \vec{p} = \vec{0}$ and $\rho \vec{g} = \vec{0}$. Relation (6) above can thus be rewritten in the following form:

$$\frac{\partial u}{\partial t} - \frac{\mu}{\rho} \Delta u = 0 \quad (7)$$

If $D = \frac{\mu}{\rho}$, the relation (7) becomes:

$$\frac{\partial u}{\partial t} - D \Delta u = 0 \quad (8)$$

Equation 8 is the diffusion equation with D, the diffusion coefficient. Thus, for unidirectional flow, equation (8) can be written as:

$$\frac{\partial u}{\partial t} - D \frac{\partial^2 u}{\partial z^2} = 0 \quad (9)$$

Since we're addressing about evaporating issue, the water wetting the surface of the Djègbadji salt marshes, i.e. considerably reducing its water content (W), we pose $u = W$ and equation (9) becomes:

$$\frac{\partial W}{\partial t} - D\frac{\partial^2 W}{\partial z^2} = 0 \qquad (10)$$

Equation (10) is well known as Fick's second law equation, which solution is obtained by making the following assumptions [55]:

(1) water flows by diffusion only;
(2) surface water content is equal to equilibrium;
(3) the diffusion coefficient and product temperature are assumed to be constant and;
(4) sample shrinkage is negligible.

Based on these assumptions, the analytical solution of Fick's second law is given by relation (11) [56-59]:

$$\frac{W-W_e}{W_0-W_e} = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}exp\left[-(2n+1)^2\frac{\pi^2 D.t}{4L^2}\right] \qquad (11)$$

The simplified form of this equation (11) is obtained by taking the first term of the series assuming $W_e = 0$. Then [58, 59]:

$$MR = \frac{W}{W_0} = \frac{8}{\pi^2}exp\left[-\frac{\pi^2 D.t}{4L^2}\right] \qquad (12)$$

and when we pose $A = \frac{8}{\pi^2}$ and $\mathrm{k} = \frac{\pi^2 D}{4L^2}$, we've obtained the equation (13) below:

$$MR = \frac{W}{W_0} = A.\exp(-kt) \qquad (13)$$

3. Results

In order to better understand capillary rise's phenomenon of salt water in the Djègbadji salt marshes and salt crystallization's mechanism at soil surface, the solution of equation (1) and the Navier Stokes equation were required. Equation (1) was solved in the MATLAB environment and the solution is described by relation (14):

$$z = -\frac{1}{a}\left[ln\left(-a\left(c+\frac{k_s * t}{n}\right)\right) - a * h_c\right] \qquad (14)$$

where k_s, is the hydraulic conductivity at soil saturation; n, soil porosity; a, rate of decrease in hydraulic conductivity; h_c, maximum height of capillary rise and finally, c, a constant set at $c = 20$.

3.1. Influence of Djègbadji Salt Marsh Soil Parameters on Capillary Rise

The influence of soil parameters such as soil saturation hydraulic conductivity (k_s), soil porosity (n), hydraulic conductivity decrease rate (a) and liquid-solid contact angle (i) on water capillary rise in the soil was analyzed.

3.2. Influence of Saturation Hydraulic Conductivity (k_s) on Capillary Rise

Figure 2 illustrates the temporal evolution (during a day) of capillary rise of water in the soil under the influence of hydraulic conductivity at saturation (k_s). The analysis reveals an increase in capillary rise for $k_s < k$, with $k = 2.10^{-4} cm.s^{-1}$, the hydraulic conductivity of unsaturated silty soil and a decrease in the level of rise for $k_s > k$. For k_s smaller than k, the capillary rise level is higher, indicating that the soil is close to saturation. On the other hand, for k_s greater than k, the level of capillary rise is lower than for k, indicating that the soil moving further away from saturation. The saturation hydraulic conductivity k_s is therefore a soil parameter that strongly influences the capillary rise of water in soils and in the Djègbadji salt marshes particularly.

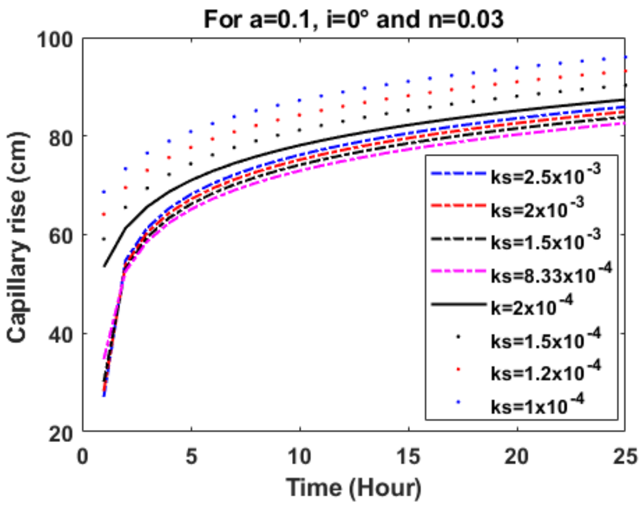

Figure 2. *Influence of hydraulic conductivity at saturation* (k_s) *on capillary rise of water in Djègbadji salt marsh soil.*

The parameter k_s is expressed in $cm.s^{-1}$ and its value will be taken equal to $1.5 \times 10^{-3} cm.s^{-1}$ for the next sections because the dry season is the favorable period for the activities of salt production in Djègbadji and, during this period, the soil is not saturated; at the angle of contact i, we assign the value 0°, because it is under this angle that the liquid perfectly wets the wall of the pore [60-62].

3.2.1. Influence of Hydraulic Conductivity Reduction Rate (a)

Figure 3 indicates the influence of the rate of decrease in hydraulic conductivity (a) on capillary rise of water in

Djègbadji salt marsh soil. During the analysis, the parameters of hydraulic conductivity at soil saturation (k_s), soil porosity (n) and liquid-solid contact angle (i) have respectively been set to $k_s = 1.5 \times 10^{-3} cm.s^{-1}, i = 0°$ and $n = 0.03$. The rate of decrease in hydraulic conductivity (a) was then varied from 10% to 60%. The analysis shows that the capillary rise of water in the soil decreases as the rate of decrease in hydraulic conductivity increases. For a hydraulic conductivity reduction rate of 10%, we observe a minimum capillary rise of 30.07 cm and a maximum rise of 83.87 cm for an average of 73.24 cm, compared with minimum, maximum and average capillary rises of 19.19 cm, 28.16 cm and 26.39 cm respectively for a hydraulic conductivity reduction rate of 60% in one day. The analysis reveals that the hydraulic conductivity rate (a) is a parameter that also strongly influences the capillary rise in Djègbadji salt marsh soils.

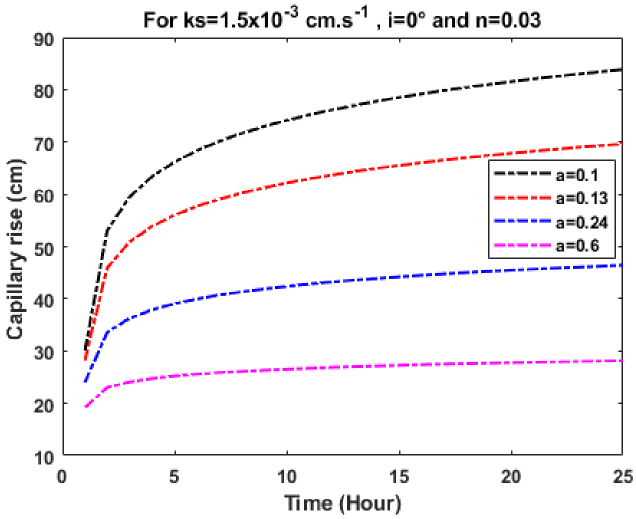

Figure 3. *Influence of the rate of decrease in hydraulic conductivity (k_s) on capillary rise of water in Djègbadji salt marsh soil.*

3.2.2. Influence of Soil Porosity (n)

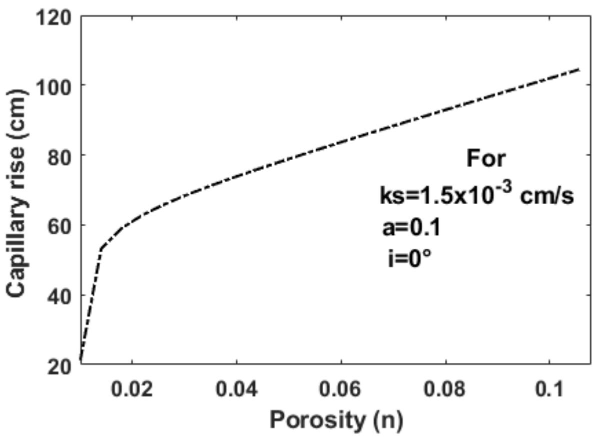

Figure 4. *Influence of soil porosity on capillary rise of water in Djègbadji salt marsh soil.*

Figure 4 illustrates the evolution of capillary rise of water in Djègbadji salt marsh soil under the influence of porosity (n). Analysis of this figure shows that capillary rise of water in Djègbadji salt marsh soil increases as porosity increases. Thus, the minimum value of capillary rise is 21.31 cm at $n = 1\%$ and its maximum value is 104.6 cm at $n = 10.6\%$ for an average of 80.19 cm at $n = 5.8\%$. The analysis thus indicates that soil porosity is also a major parameter influencing capillary rise of water in Djègbadji salt marsh soil.

3.2.3. Influence of Liquid-solid Contact Angle (i)

Figure 5 shows the evolution of capillary rise of water in Djègbadji salt marsh soil under the influence of the liquid-solid contact angle (i). Analysis of this figure shows an oscillatory (sawtooth) upward trend in capillary rise, with a minimum value of 27.86 cm and a maximum value of 81.53 cm, for an average of 60.33 cm. This parameter therefore also influences the phenomenon of capillary rise in the soil.

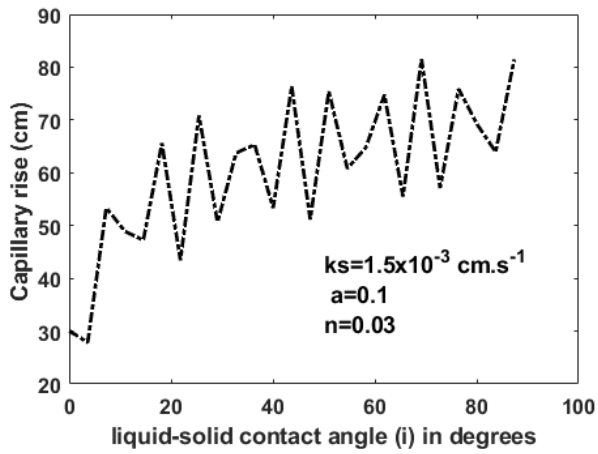

Figure 5. *Influence of variation in liquid-solid contact angle on capillary rise of water in Djègbadji salt marsh soil.*

3.2.4. Salt Crystallization on the Surface of Djègbadji Salt Marshes

Equation (13) is the Henderson and Pabis drying model obtained by modification of the Page model in 1962 [63]. From the analysis of this equation (13) involving the function (e^{-x}), it emerges that the water content of the soil surface in the Djègbadji salt marshes decreases over time. This implies a probable progressive oversaturation of the soil with salt, culminating in evapotranspiration-induced salt precipitation followed by accumulation on and near the soil surface of these salt marshes.

4. Discussion

Djègbadji is a wetland in the municipality of Ouidah [64], which, like any other area of this type, undergoes cycles of moistening and drying resulting in transient interactions between groundwater and surface water [17]. As Shah et al, (2011) [41] and van der Zee et al, (2014) [65] have already pointed out, groundwater can be a real source of water and salt for these wetlands. In fact, dissolved salts in the shallow groundwater at Djègbadji rises to the surface by capillary action, creating an induced flow towards the root zone where the salt accumulates. As shown in the analysis of Figures 2, 3, 4 and 5, the upwelling of a fluid (water) by capillarity in the soil is a phenomenon that is influenced by several soil parameters such as the saturated hydraulic conductivity of the soil (k_s), the porosity of the soil (n), the rate of decrease of the hydraulic conductivity (a) and the liquid-solid contact angle (i), i.e. it varies according to the nature of the soil characterized by the values of these parameters. In addition, the profiles in Figures 2, 3 and 4 are identical to those obtained by Duarte et al, (1996) [32] in their study of capillary rise in open tubes. Moreover, the results from the analysis of Figure 2 differed from those found in 2015 by Coulibaly [66] regarding the infiltration of water in the soil, which is a phenomenon opposed to water capillary rise in the soil. In Djègbadji salt marshes, water is able to rise by capillary action from the shallow $50-60\ cm$ brackish water table to the soil surface [16], carrying with it the salt dissolved in it. During drought (a favorable period for salt production in Djègbadji), the demand for water from the atmosphere met by evapotranspiration is generally higher than the flow of liquid water [67]. The transport of salt from groundwater to the surface follows an increase in liquid water saturation at the surface. This saturation is followed by salt crystallization as saline efflorescence and salt accumulation on and around the soil surface is governed by its water content values [66].

In addition, it should be noted that the climatic conditions on the site of Djègbadji (mean temperature: $28.04°C$; mean humidity: 81.04%; mean radiation: $50.21\ kWh.m^{-2}$; mean insolation: $4.98\ kWh.m^{-2}$; mean wind speed: $4.24\ m.s^{-1}$ [15]; mean net radiation: $401.35\ W.m^{-2}$), are favourable for soil surface drying. Indeed, the climatic conditions listed above contribute to the gradual loss of soil moisture over the time. This loss of humidity leads to the oversaturation of the soil, to a certain precipitation of the salt followed by its accumulation on the soil surface. This could justify obtaining brine at Djègbadji by leaching sand from soil scraping.

Equation 13 provides a better understanding of salt crystallization at the Djègbadji site in Benin. It highlights a progressive decrease in water content at the soil surface over time. This reduction leads to saturation, or even supersaturation, of the upper soil layers with salt, which, under the effect of evapotranspiration, results in salt precipitation followed by its accumulation. This phenomenon likely explains the extraction of brine through the leaching of saline soils in this region.

Similar results were obtained in 2008 by Guglielmini et al. [68] and in 2014 by Zhang et al. [69]. In their work, Guglielmini et al. (2008) [68] considered the evaporation rate as constant and the liquid saturation in the porous medium as uniform, varying only with time. Under these conditions, they found that salt tends to accumulate in a narrow region adjacent to the surface where evaporation occurs, while in the rest of the site, salt remains evenly distributed and decreases over time due to a purely convective effect. Similarly, Zhang et al. [69] observed through their simulations that the presence of a hydraulic connection between the soil's surface layer and the underground water source promotes vaporization near the surface, with salt exclusively depositing as efflorescence. In contrast, in the absence of such a hydraulic connection, the vaporization front moves downward, and salt settles as subflorescence. Efflorescence, being more abundant, has a significantly greater impact on evaporation than subflorescence during the soil drying process. The characterization of the evaporation process in bare saline soils, whether or not they have a fixed water table, can be achieved by identifying the different evaporation stages based on the location of the vaporization front and salt accumulation.

During salt crystallization, the phenomenon depends on heat transfer [70], whose coefficient is itself influenced by free convection in a liquid water film and a saline vapor gas [71-79]. The phase transition rate is closely linked to the thickness of the liquid layer available in the salt solution [80]. Furthermore, the hydrophilicity of the surface significantly affects the evaporation rate [80-83], as does the location of hydrated salt crystal formation. When significant heat fluxes are present within the droplet and the thin layer, natural convection occurs, leading to enhanced evaporation [84-87]. Initially, an increase in supersaturation is observed (the actual concentration increases over time). Crystallization behavior is influenced by the location of the first crystal nucleus, the rate of evaporation and crystallization, and the temperature distribution at the free surface of the layer [88]. The phenomena of capillary rise and crystallization of salt on the surface of the salt marshes of Djègbadji site have ensured the continuation of food salt production in this district for centuries.

Iodized salt helps address iodine deficiency and associated disorders; plays an important role in physical and mental activity for adults, in the normal growth and development of the fetus, infant and child [89]. Moreover, salt production in Djègbadji is a revenue generating activity for the salt workers in this locality [1]. It thus contributes to the achievement of the Sustainable Development Goals, in particular SDG 8, which stipulates "to promote sustained, shared and sustainable economic growth, full productive employment and decent work for all" and SDG 9, which stipulates that "build resilient infrastructure, promote sustainable industrialization that benefits everyone, and encourage innovation."

5. Conclusions

A solution of the one-dimensional Terzaghi equation governing the capillary rise of water in soil was obtained and the capillary rise of brackish water in the Djègbadji salt marshes was analyzed. The appearance of fine salt crystals on and near the soil surface maybe due to the evapotranspiration on soils soaked in brackish water. In short, the phenomena of capillary rise and crystallization in the process of salt precipitation and accumulation on the soil surface are important for understanding the process of salinization rate at the Djègbadji salt marsh.

Abbreviations

h_a	Air Inlet Head
h_c	Maximum Height
γ	Surface Tension
η	Kinematic Viscosity of Water
g	Earth's Gravity
ρ_w	Density of Water
ρ	Density
μ	Dynamic Viscosity
$\vec{p}$	Pressure Field
$\vec{g}$	Gravitational Force
D	Diffusion Coefficient
W	Water Content
t	Time
MR	Moisture Ratio
z	Capillary Rise
k_s	Saturated Hydraulic Conductivity
n	Porosity
a	Hydraulic Conductivity
i	Liquid-solid Contact Angle
k	Hydraulic Conductivity of Unsaturated Silty Soil
SDG	Sustainable Development Goals

Author Contributions

Armel Vitouley: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft

Guy Hervé Houngnè: Conceptualization, Data curation, Formal Analysis, Methodology, Software, Supervision, Validation, Visualization, Writing – review & editing

Gabin Koto N'gobi: Conceptualization, Data curation, Formal Analysis, Methodology, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing

Julien Adounkpè: Formal Analysis, Funding acquisition, Investigation, Resources, Supervision, Validation, Writing – review & editing

Waliou Amoussa Hounkpatin: Validation, Visualization, Writing – review & editing

Clément Ahouannou: Investigation, Supervision, Validation, Visualization

Basile Kounouhéwa: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Methodology, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing

Funding

The authors gratefully acknowledge funding from the Federal German Government, particularly its Ministry of Higher Education and Scientific Research BMBF, through the FOCUSED-Benin project, the work package V of the YES PV NIGBEN project, Grant TTB/B1806.05.18.

Conflicts of Interest

The authors declare no conflicts of interest.

References

[1] Teka, O., Houessou, L. G., Djossa, B. A., Bachmann, Y., Oumorou, M., Sinsin, B., 2018. Mangroves in Benin, West Africa: threats, uses and conservation opportunities Environment, Development and Sustainability 21(3) 1153-1169. https://doi.org/10.1007/s10668-017-0075-x

[2] Automne, A. C. A. L., Montoroi, J. P., Mane, A., and Niokane, M., 2021. Traditional solar salt production in Lower Casamance (Senegal): Environmental and socioeconomic benefits and disadvantages. African Journal of Agricultural Research 17(2) 302-309 https://doi.org/10.5897/AJAR2018.13815

[3] Francisco, A. B., Llamar, N. L., and Chávez, E. H., 2022. Salt-making as a stunting enterprise and practice: the case of ilocos sur, philippines. Social Sciences, Humanities and Education Journal (SHE Journal) 3(2) 159–169. http://doi.org/10.25273/she.v3i2.12683

[4] Xing, X., Zhu, Y., Yuan, Z., Xiao, L., Liu, X., Chen, L., Xia, Q., and Liu, B., 2021. Predicting mining-induced dynamic deformations for drilling solution rock salt mine based on probability integral method and weibull temporal function. International Journal of Remote Sensing, 42(2) 639-671. https://doi.org/10.1080/01431161.2020.1813345

[5] Szűcs, E., Gönczy, S., Bozsó, I., Bányai, L., Szakacs, A., Szárnya, C., and Wesztergom, V., 2021. Evolution of surface deformation related to salt-extraction-caused sinkholes in Solotvyno (Ukraine) revealed by Sentinel-1 radar interferometry, Nat. Hazards Earth Syst. Sci., 21(3) 977–993. https://doi.org/10.5194/nhess-21-977-2021

[6] Majeed, Y., Emad, M. Z., Rehman G., & Arshad, M., 2019. Block Extraction of Himalayan Rock Salt by Applying Conventional Dimension Stone Quarrying Techniques. J Min Sci 55 610–625. https://doi.org/10.1134/S1062739119045965

[7] Cooper, A. H., 2020. Geological hazards from salt mining, brine extraction and natural salt dissolution in the UK. in Giles, D. P. & Griffiths, J. S. (eds) 2020 Geological Hazards in the UK: Their Occurrence, Monitoring and Mitigation – Engineering Group Working Party Report. Geological Society, London, Engineering Geology Special Publications 29(1) 369–387 https://doi.org/10.1144/EGSP29.14

[8] Korovessis, N. A., & Lekkas, T. D., 2009. Solar Saltworks' wetland function. Global NEST Journal 11(1) 49-57 https://doi.org/10.30955/gnj.000575

[9] Javor, B., J., 2002. Industrial microbiology of solar salt production Journal of Industrial Microbiology and Biotechnology 28(1) 42–47 https://doi.org/10.1038/sj/jim/7000173

[10] Mensah, B., and Bayitse, R., 2006. Solar salt technologyin ghana –a case study of small scale salt winning process. Ghana J. Sci. 46 99-109 https://doi.org/10.4314/gjs.v46i1.15921

[11] Yémoa, A. L., Adissoda, C. M., Agbokponto, E., and Amoussou, A., 2022. Salt Production and Availability of Iodized Salt in the Municipality of Sèmè-Kpodji in 2022. Nutri Food Sci Int J. 11(4) 001-007. https://dx.doi.org/10.19080/NFSIJ.2022.11.555817

[12] Fall, A. C. A. L., Montoroi, J. P., Mane, A., and Niokane, M., 2021. Traditional solar salt production in Lower Casamance (Senegal): Environmental and socioeconomic benefits and disadvantages. African Journal of Agricultural Research 17(2) 302-309 https://dx.doi.org/10.5897/AJAR2018.13815

[13] Adounkpe, J., Agboton, C., Hounkpatin, W. A., Kounouhewa, B., Ahouannou, C., and Sinsin, B., 2021. Qualitative Assessment of Table Salt Production Techniques in Southern Benin Republic, and Related Mangrove Destruction and Health Issues. Food and Nutrition Sciences 12(7) 759-773. https://doi.org/10.4236/fns.2021.127057

[14] Padonou, E. A., Totin, E., Akakpo, B. A., Gbenontin, E., and Kolawole, M. A., 2022. Determinants of the abandonment of improved stoves in salt production systems in Djègbadji, South Benin. Bulletin de la Recherche Agronomique du Bénin (BRAB) 32(01) 1-10(translated from French). https://www.researchgate.net/publication/362717172

[15] Adounkpe, J., Houngue, G. H., Hounkpatin, W. A., Vitouley, A., Ahouannou, C., & Kounouhewa, B., 2021. Reduction of post-harvest losses through estimation of open air-drying period of agricultural products of mass consumption: case of Benin. International Journal of Environmental Studies 79(5) 837-851. https://doi.org/10.1080/00207233.2021.1965794

[16] Volkoff, B., 1965. Study of the soils of the Guézin-Ouidah coastal region, Office of Overseas Scientific and Technical Research, Mission O R S T O M Dahomey p155 (Translated from French).

[17] Liu, B., Zhao, W., Wen, Z., Yang, Y., Chang, X., Yang, Q., Meng, Y., Liu, C., 2018. Mechanisms and feedbacks for evapotranspiration-induced salt accumulation and precipitation in an arid wetland of China. Journal of Hydrology 568 403-415 https://doi.org/10.1016/j.jhydrol.2018.11.004

[18] Lu, N., and Likos, W. J., 2004. Rate of Capillary Rise in Soil. Journal of Geotechnical and Geoenvironmental Engineering, 130(6) 646-650. https://doi.org/10.1061/(ASCE)1090-0241

[19] Miller, R. J., and Low, P. F., 1963. Threshold Gradient for Water Flow in Clay Systems1. Soil Science Society of America Journal 27(6) 605–609. https://doi.org/10.2136/sssaj1963.03615995002700060013x

[20] Zhang, Z., Tian, G., and Han, L., 2020. Influence of Chemical Osmosis on Solute Transport and Fluid Velocity in Clay Soils Open Chemistry 18(1) 232-238 https://doi.org/10.1515/chem-2020-0026

[21] Letey, J., Kemper, W. D., and Noonan, L., 1969. The Effect of Osmotic Pressure Gradients on Water Movement in Unsaturated Soil1. Soil Science Society of America Journal 33(1) 15–18 https://doi.org/10.2136/sssaj1969.03615995003300010010x

[22] Mahdavi, S. M., Neyshabouri, M. R., Fujimaki, H., 2018. Water vapour transport in a soil column in the presence of an osmotic gradient. Geoderma 315 199–207. https://doi.org/10.1016/j.geoderma.2017.11.031

[23] Sato, K., and Iwasa, Y., 2000. Groundwater Flow under a Temperature Gradient. Groundwater Hydraulics pp 99-113. https://doi.org/10.1007/978-4-431-53959-9_4

[24] Joshue, W. D., and Jong, E. D., 1973. Soil moisture movement under temperature gradients. Can. J. Soil Sci. 53(1) 49-57 https://doi.org/10.4141/cjss73-00

[25] Rong, R., Juanjuan, M., Qiyun, C., Lijian, Z., Xianghong, G., Xihuan, S., 2017. An Investigation into the Effects of Temperature Gradient on the Soil Water–Salt Transfer with Evaporation. Water 9(7) 456. https://doi.org/10.3390/w9070456

[26] Zhang, C., and Liu, E., 2023. Experimental study on moisture and heat migration and deformation properties of unsaturated soil column under a temperature gradient during rainfall infiltration. Plos one 18(6) https://doi.org/10.1371/journal.pone.0286973

[27] Tamanna, P., and Attar, S., 2018. Electrossmotic flow and electroosmosis in soil. International Journal of Fauna and Biological Studies 5(2) 74-77.

[28] Parent, S. E., 2020. Soil mechanics. GAE-1000 Agri-environmental engineering concepts (translated from french). https://creativecommons.org/licences/by/4.0/

[29] Allan, F. R., and Cherry, J. A., 1979. Groundwater project. University of Guelph, Guelph, Ontario, Canada https://fc79.gw-project.org/about/

[30] Batchelor, G. K., 1970. An Introduction to Fluid Dynamics (Cambridge University Press 1970).

[31] Landau, L. D., & Lifshitz, E. M., 2013. Fluid Mechanics: Landau and Lifshitz: Course of Theoretical Physics, Volume 6 6.

[32] Duarte, A. A., Strier, D. E., and Zanette, D. H., 1996. The rise of a liquid in a capillary tube revisited: A hydrodynamical approach. American Journal of Physics 64(4) 413-418 http://dx.doi.org/10.1119/1.18256

[33] Hellemans, J., Forrez, P., and De Wilde, R., 1980. Experiment illustrating Bernoulli's equation and Hagen-Poiseuille's law. Am. J. Phys. 48(3) 254-255 https://doi.org/10.1119/1.12154

[34] Menon, V. J., and Agrawal, D. C., 1987. Newton's law of motion for variable mass systems applied to capillary. Am. J. Phys. 55(1) 63-67 https://doi.org/10.1119/1.15312

[35] Scheie, P. O., 1989. The upward force on liquid in a capillary tube. Am. J. Phys. 57(3) 279-280. https://doi.org/10.1119/1.16056

[36] Case, C., M., 1990. Rate of rise of liquid in a capillary tube-revisited. Am. J. Phys. 58(9) 888-889. http://dx.doi.org/10.1119/1.16491

[37] McCaughan, J. B. T., 1992. Comment on: The upward force on liquid in a capillary tube. Am. J. Phys. 60(1) 87-88 https://doi.org/10.1119/1.17050

[38] Alireza, A., Majid, A., Mehdi, H., 2022. Controlling salt crystallization in evaporating thin films of colloidal liquids. Colloids and Surfaces A: Physicochemical and Engineering Aspects 636 128094. https://doi.org/10.1016/j.colsurfa.2021.128094

[39] Mancigotti, S., & Hamilton, A., 2017. Salt crystallisation in pores: The effect of crystal growth rate on damage WIT. Transactions on the Built Environment 171 207-214 https://doi.org/10.2495/STR170181

[40] Veran-Tissoires, S., Marcoux, M., and Prat, M., 2012. Discrete Salt Crystallization at the Surface of a Porous Medium. Phys. Rev. Lett. 108(5) 054502. https://doi.org/10.1103/PhysRevLett.108.054502

[41] Shah, S. H. H., Vervoort, R. W., Suweis, S., Guswa, A. J., Rinaldo, A., van der Zee, S. E. A. T. M., 2011. Stochastic modeling of salt accumulation in the root zone due to capillary flux from brackish groundwater. Water Resour. Res. 47(9). https://doi.org/10.1029/2010WR009790

[42] Norouzi, R. M., Shokri, N., 2012. Nonlinear effects of salt concentrations on evaporation from porous media. Geophys. Res. Lett. 39(4). https://dx.doi.org/10.1029/2011GL050763

[43] Nachshon, U., Weisbrod, N., Dragila, M. I., Grader, A., 2011. Combined evaporation and salt precipitation in homogeneous and heterogeneous porous media. Water Resour. Res. 47(3) https://doi.org/10.1029/2010WR009677

[44] Bachirou, Z. S., & Vissin, E. W., 2019. Water Resource Management and Pathological Risk: Water Resource Management and Pathological Risks in the District of Djègbadji, Ouidah Municipality, Benin. European University Editions. 128 pages. (Translated from french).

[45] Sinzogan, F., Adje, A. H. C., Degbe, C. G. E., Edea, O. E., Djihouessi, B., Sossou, A. C. J., Dassi, E., Akitikpa, I. B., Yaï, C. P., Jimaja, P., Aïna, M. P., Kelome, N., Lougbegnon, O. T., Codo, F. P., Alassane, A., Sohou, Z., Hedible, S. C., Ndione, J. A., Amoussou, A., Dacosta, R., Neumann, C., Vinaccia, M., 2020. Report: state of Benin's marine environment. 126p (Translated from french).

[46] Yantikoua, S., Laïbi, R., Adechina, R., Kaki, C., Mama, D., & Laleye, P., 2021. Hydrological dynamics and morpho-sedimentary evolution of Lake Ahémé in south-west Benin. European Scientific Journal, ESJ, 17(10) 77. https://doi.org/10.19044/esj.2021.v17n10p77 (Translated from french).

[47] Boko, M., 1988. Climates and rural communities in Benin: Climatic rhythms and development rhythms. (Doctoral dissertation, Dijon) Climatology Research Center 2 607p (Translated from french).

[48] Terzaghi, K., 1943. Theoretical Soil Mechanics. Wiley, New York p529. http://dx.doi.org/10.1002/9780470172766

[49] Qiang, L., Noriyuki, Y., Jiali, M., Jiaguo, R., 2014. An approach for quick estimation of maximum height of capillary rise Soils and Foundations 54(6) 1241–1245. http://dx.doi.org/10.1016/j.sandf.2014.11.017

[50] Eisenlohr, L., 1989. Determination of the saturation hydraulic conductivity (KS) of acid sulfate soils from Basse Casamance (Senegal) by the double ring method or Muntz principle: influence. Paris: Paris 6; Nancy 1; Université de Franche-Comté; INA ; ENSA, 67 p. Thesis. DEA: Pedology, Paris 6; Nancy 1; Université de Franche-Comté; INA; ENSA. 1989/09. (Translated from french).

[51] Avakoudjo, J., Kouelo, A. F., Kindomihou, V., Ambouta, K., Sinsin, B., 2015. Effect of water erosion on soil physico-chemical characteristics of erosion zones (dongas) in the Commune of Karimama, Benin Agronomie Africaine 27(2) 127 - 143 (Translated from French).

[52] Gresho, P. M., 1991. Incompressible fluid dynamics: some fundamental formulation Issues. Annu. Rev. Fluid Mech. 23(1) 413-53.

[53] Bonnefoy, O., 2021. Fluid mechanics and transfers Version: 6.3 of September 6, 2021. Student version.

[54] Voronovich, A. G., 2018. A complex scalar form of the incompressible Navier–Stokes equations. Waves in Random and Complex Media 2018 1–12 https://doi.org/10.1080/17455030.2018.1524184

[55] Mühlbauer, W., and Müller, J., 2020. Drying kinetics and quality of agricultural products. Drying Atlas, (Cambridge: Woodhead Publishing) 1 9–35 https://doi.org/10.1016/B978-0-12-818162-1.00003-1

[56] Crank, J., 1975. Mathematics of diffusion, 2nd ed., Oxford University Press, London 69-88.

[57] Rao, M. A., and Rizvi, S. S. H., 1986. Engineering Properties of Food. Food science and technology (Marcel Dekker, Inc.), New York.

[58] Hawlader, M. N. A., Uddin, M. S., Ho, J. C., and Teng, A. B. W., 1991. Drying characteristics of tomatoes Journal of Food Engineering 14(4) 259-268. https://doi.org/10.1016/0260-8774(91)90017-M

[59] Doymaz, I., 2007. The kinetics of forced convective air-drying of pumpkin slices. Journal of Food Engineering 79(1) 243–248 https://doi.org/10.1016/j.jfoodeng.2006.01.049

[60] Bruand, A., Coquet, Y., 2005. Soils and the water cycle pp.345-363 ffhal 00090203 (Translated from French).

[61] Brouyère, S., 2007. Study and modelling of solute transport and trapping in a variably saturated underground environment, PhD thesis from the University of Liège p 640 (Translated from French).

[62] Kenouche, S., 2016. Surface physical chemistry and heterogeneous catalysis Cours and applications p92 (Translated from French).

[63] Henderson, S. M., and Pabis, S., 1962. Grain drying theory: IV. The effect of air flow rate on the drying index Journal of Agricultural Engineering Research 7(2) 85-89.

[64] Akotossode, C. C., Achoh, M. E., Agadjihouede, H., Vodougnon, H. M. B., Amadou A. S., and Tchabi, V. I., 2018. Current state of the natural resources of djègbadji and adounko (site ramsar 1017) in south-west benin (west africa) in the climatic change context J. Rech. Sci. Univ. Lomé (Togo) 20(2) 19-33 https://www.researchgate.net/publication/329969720

[65] van der Zee, S. E. A. T. M., Shah, S. H. H., Vervoort, R. W., 2014. Root zone salinity and sodicity under seasonal rainfall due to feedback of decreasing hydraulic conductivity Water Resources Research 50(12) 9432-9446 https://doi.org/10.1002/2013WR015208

[66] Coulibaly, F., 2015. Characterization of the hydrodynamic properties of the soils of the kamboinse crop-news experimental device Master's thesis in water and environmental engineering, option: Hydraulic Infrastructures and Networks (HIN); p63 (Translated from French). http://documentation.2ie-edu.org/cdi2ie/doc_num.php?explnum_id=1957

[67] Huffman, R. L., Delmar, D. F., William, J. E., and Stephen., R. W., 2013. Chapter 4: Evaporation and Evapotranspiration. Soil and Water Conservation Engineering 7 55-79 https://doi.org/10.13031/swce.2013.4

[68] Guglielmini, L., Gontcharov, A., Aldykiewicz, A. J., Stone, H. A., 2008. Drying of salt solutions in porous materials: Intermediate-time dynamics and efflorescence Physics of Fluids 20(7) 77101-0 https://dx.doi.org/10.1063/1.2954037

[69] Zhang, C., Li, L., and Lockington, D., 2014. Numerical study of evaporation-induced salt accumulation and precipitation in bare saline soils: Mechanism and feedback Water Resour. Res. 50(10) 8084–8106 https://doi.org/10.1002/2013WR015127

[70] Nakoryakov, V. E., Misyura, S. Ya., Elistratov, S. L., Dekhtyar R. A., 2014. Two-phase nonisothermal flows of LiBr water solution in minichannels Journal of Engineering Thermophysics 23(4) 257–263 https://doi.org/10.1134/S1810232814040018

[71] Misyura, S., Y., & Donskoy, I. G., 2016. Dissociation of natural and artificial gas hydrate Chemical Engineering Science, 148 65-77 https://doi.org/10.1016/j.ces.2016.03.021

[72] Misyura, S. Y., 2016. Efficiency of methane hydrate combustion for different types of oxidizer flow Energy 103 430-439 https://doi.org/10.1016/j.energy.2016.03.005

[73] Lebedev, V. P., Lemanov, V. V., Misyura, S. Y., and Terekhov, V. I., 1993. Effect of flow acceleration and initial turbulence level on velocity fluctuations Fluid Dyn 28(5) 624–629 https://doi.org/10.1007/BF01050044

[74] Misyura, S. Y., 2017. Evaporation of a sessile water drop and a drop of aqueous salt solution Scientific reports 7(1) 14759 https://doi.org/10.1038/s41598-017-15175-1

[75] Nakoryakov, V. E., Mezentsev, I. V., Meleshkin, A. V., and Elistratov, D. S., 2015. Visualization of physical processes occurring on liquid nitrogen injection into water J. Engin. Thermophys 24 322–329. https://doi.org/10.1134/S1810232815040037

[76] Nakoryakov, V. E., Misyura, S. Y., Elistratov, S. L., Manakov A. Yu., Shubnikov, A. E., 2013. Combustion of methane hydrates J. Engin. Thermophys. 22(2) 87–92. https://doi.org/10.1134/S181023281302001X

[77] Misyura S Y 2013 Effect of heat transfer on the kinetics of methane hydrate dissociation Chemical Physics Letters 583 34-37. https://dx.doi.org/10.1016/j.cplett.2013.08.010

[78] Meleshkin, A. V., Bartashevich, M. V., Glezer, V. V., 2019. Investigation of the effect of operating parameters on the synthesis of gas hydrate by the method based on self-organizing process of boiling-condensation of a hydrate-forming gas in the volume of water Applied Surface Science 493 847-851 https://doi.org/10.1016/j.apsusc.2019.06.276

[79] Misyura, S., Meleshkin, A., Markovich, D. M., Kuibin, P. A., Vorobyev, M. A., 2019. Droplet desorption modes at high heat flux EPJ Web of Conferences 196 00002 https://doi.org/10.1051/epjconf/201919600002

[80] Misyura, S. Y., Volkov, R. S., Filatova, A. S., 2018 Interaction of two drops at different temperatures: The role of thermocapillary convection and surfactant. Colloids and Surfaces A. Physicochemical and Engineering Aspects 559 275–283 https://doi.org/10.1016/j.colsurfa.2018.09.063

[81] Kuznetsov, G. V., Feoktistov, D. V., Orlova, E. G., Batishcheva, K., & Ilenok, S. S., 2019. Unification of the textures formed on aluminum after laser treatment. Applied Surface Science 469 974-982 https://doi.org/10.1016/j.apsusc.2018.11.046

[82] Misyura, S. Y., 2014. Nucleate boiling in bidistillate droplets International Journal of Heat and Mass Transfer 71 197-205 https://dx.doi.org/10.1016/j.ijheatmasstransfer.2013.12.013

[83] Orlova, E. G., Feoktistov, D. V., Kuznetsov, G. V., Ponomarev, K. O., 2018. Spreading of a distilled water droplet over polished and laser-treated aluminum surfaces European Journal of Mechanics - B/Fluids 68 118–127 https://doi.org/10.1016/j.euromechflu.2017.12.002

[84] Misyura, S. Y., 2018. Evaporation and heat and mass transfer of a sessile drop of aqueous salt solution on heated wall. International Journal of Heat and Mass Transfer 116 667-674 https://doi.org/10.1016/j.ijheatmasstransfer.2017.09.018

[85] Misyura, S. Y., 2018. Effect of various key factors on the law of droplet evaporation on the heated horizontal wall. Chemical Engineering Research and Design 129 306-313 https://doi.org/10.1016/j.cherd.2017.11.033

[86] Antonov, D. V., Kuznetsov, G. V., Piskunov, M. V., Vysokomornaya, O. V., & Yan, W. M., 2019. Warming-up and evaporation characteristics of homogeneous and heterogeneous water droplets International Journal of Heat and Mass Transfer 138 1061-1074 https://doi.org/10.1016/j.ijheatmasstransfer.2019.04.131

[87] Misyura, S. Y., 2019. The influence of convection on heat transfer in a water layer on a heated structured wall International Communications in Heat and Mass Transfer 102 14-21 https://doi.org/10.1016/j.icheatmasstransfer.2019.01.010

[88] Misyura, S. Y., and Morozov, V. S., 2019. Crystallization of Salt Solutions on Surface of Droplet and Layer Journal of Engineering Thermophysics 28(3) 381–391 https://doi.org/10.1134/S1810232819030081

[89] Mizéhoun-Adissoda, C., Yémoa, A., Jerome, C. S., Biobou, A., Alouki, K., Azandjèmé, C., Houngla, J. H., Houinato, D., Bigot, A., Desport, J. C., 2018. Iodine content and microbiological quality of food salts marketed in Benin Clinical Nutrition and Metabolism 32(2) 102-108 (Translated from French). https://doi.org/10.1016/j.nupar.2018.01.001