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Salt water evaporation droplet: comparison between NaCl and KCl droplet posed on the same substrate

[1]H. ZOUAGHI, [2]S. HARMAND and [3]S. BEN JABRALLAH
[1]National Engineering School of Monastir, Avenue Ibn El Jazzar, 5019, Monastir, Tunisia
[2]University of Lille Nord, UVHC – LAMIH UMR CNRS 8201, Mont Houy, Valenciennes, Cedex 09, 59300, France
[3]Sciences Faculty of Bizerte – Laboratory LETTM, Zarzouna, 7021 Bizerte – Tunisia
hibazouaghi@yahoo.fr , *souad.harmand@univ-valenciennes.fr, and sadokjabrallah@yahoo.fr*

Abstract: This study focuses on the evaporation of a salt water droplet. Two types of salts are used: sodium chloride (NaCl) and potassium chloride (KCl). The droplet is exposed to a heat flux at 30°C. However, the substrate, on which the drop is placed, is maintained at ambient temperature. Three substrates are used. These are stainless steel, copper, and vitreous carbon.

The initial contact angle of the droplet is measured before evaporation begins. The evaporated flow rate is determined for each droplet and substrate.

The variation of the droplet diameter during its evaporation indicates that this is different from one substrate to another. After evaporation, a deposit of the saline droplet forms. A comparison of the different forms of deposit is established.

1. Introduction

The droplet evaporation represents a very important sector in several fields. Lu *et al.,* [1] indicate that evaporation of a drop is important in conventional and high-tech processes such as metallurgy, nuclear thermal management, and cooling of microelectronic packages. Anchor jet printing, spray cooling, and several other applications in the field of medicine have been mentioned by Yu *et al.* [2]. Other applications have been indicated by Tuan *et al.,* [3,4] such as the evaporation of a sessile drop of nanofluids in many fields such as structuring, delivery of active reagent, film coating And detergency; Intensive research has been conducted to study the effect of colloidal and nanometric particles on the evaporation of droplets.

Several other parameters have been the subject of many studies of the droplet evaporation. Other authors have studied the effect of the substrate on which droplet is posed (Lopes et al., [5], Dunn et al., [6]), in particular, the thermal conductivity of the heated substrate. These studies show that the thermal conductivity of the substrate has a great influence in improving evaporation. When the substrate is preheated, the higher its thermal conductivity, the greater is the evaporated flow rate. For this reason, it is advisable to use metal substrates with high thermal conductivity.

Other studies have focused on the effect of angle and line of contact on the droplet evaporation (Grandas *et al.,* [7], Bernardin *et al.,* [8], Xie et *al.* [9] and Chandra *et al.* [10]). They found that the contact angle is also important in evaporation. When it is low, the evaporated flow is large and vice versa. In order to improve the evaporation, it is advisable to use substrates whose contact angle is low, the wettability surface between the drop and the substrate is large, which makes it possible to obtain a better yield.

The droplet evaporation also concerns the study of deposits after evaporation. In order to better understand the distribution of particles after the total disappearance of the water or volatile matter contained in the droplets, a MARANGONI calculation has allowed some to better understand the direction of particles movement during evaporation.

This study deals with the evaporation of salt water droplet having a NaCl and KCl having the same concentration of 0,1% posed on different substrates. The pure water droplet is taken as a reference. The substrates used are three: stainless steel, vitreous carbon and copper. Several studies are focused on heating the substrate. In this study, it's the air around the droplet which is preheated at 30°C. The substrate is maintained at ambient temperature.

The initial volume of the droplet is fixed on 10µl at an ambient temperature of 18°C. The air around droplet is heated to 30°C in average. The study of evaporation kinetic of the droplet as function of different substrates is made. The diameter variation is determined for each droplet and substrate. After evaporation, the salt water droplet deposit is observed.

2. Experimental device

An experimental device is made (Figure 1). The aim is to analyze the evaporation kinetics, temperature variation, and the diameter decrease of the droplet during its evaporation. This device comprises:

- A micro balance allows measuring the mass evolution as function of the time for each substrate. The micro-balance has a precision of 10^{-6}g.
- Two heating resistors, to heat the air around the droplet at 30°C on average.
- An infrared camera dedicated to thermal measurements on the droplet during its evaporation.
- Syringe pump: giving the same droplet volume set at 10µl.
- Sapphire cover: to have a good view of the thermal measurements using the infrared camera.

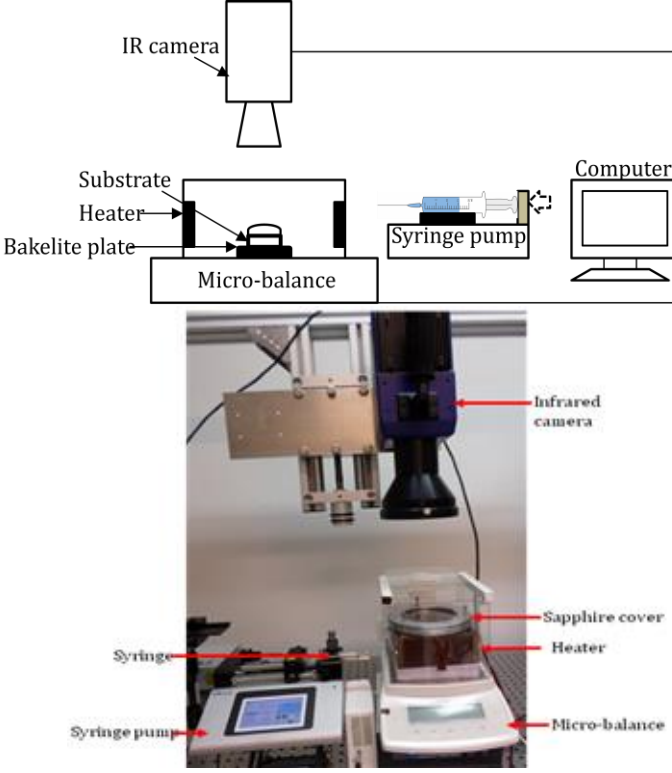


Figure 1: Experimental device

Three substrates are used. They are chosen for their different physical properties which are presented in Table 1. All of the substrates had the same physical dimension of 1cm×1cm×0,2cm (length × breadth × thickness).

Table 1: Physical properties of the five substrates at ambient temperature and pressure

Parameter	Density (kg/m3)	Specific heat capacity (J/kg.K)	Thermal conductivity(W/mK)	Emissivity
Symbol	ρ	Cp	k	ε
Stainless steel	7.9×103	500	15	0.35
Vitreous Carbon	1.5×103	-	2.6	-
Copper	8.96×103	380	390	0.07

Two types of salt water are compared. It’s the sodium chloride (NaCl) and the potassium chloride (KCl) at the same concentration of 0,1%. The initial droplet volume is fixed on 10µl at an ambient temperature of 18°C in average.

The experimental device used to measure the initial contact angle of the droplet is presented in Figure 2. The different substrates and droplets are used at ambient temperature.

A CCD camera is connected to a computer to take droplet photo. The contact angle is then calculated using software.

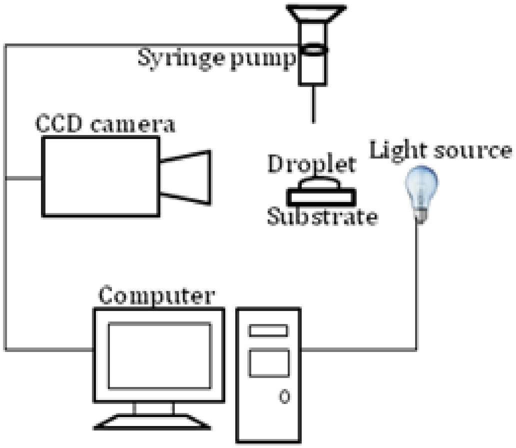


Figure 2: Experimental device used for contact angle

After adjustment of the light, the camera focal distance is set relative to the substrate, in order to have a crisp, clear image.

A photo is then taken; the image processing is started using the software FTA32. This software can determine the left and right or average contact angle of the droplet. Tests are repeated 3 times and sometimes more until obtaining three similar results. Then, the average of right and left contact angles is calculated for the different substrates.

3. Results and discussion

This study is divided into three parts. For NaCl, KCl and the pure water droplet, the evaporated flow and the diameter variation are determined for the three substrates (stainless steel, vitreous carbon and copper), on which the droplet is posed. After evaporation, a deposit is examined for each substrate.

The variation of the evaporated mass flow of NaCl, KCl and pure water droplet is presented in figure 3.

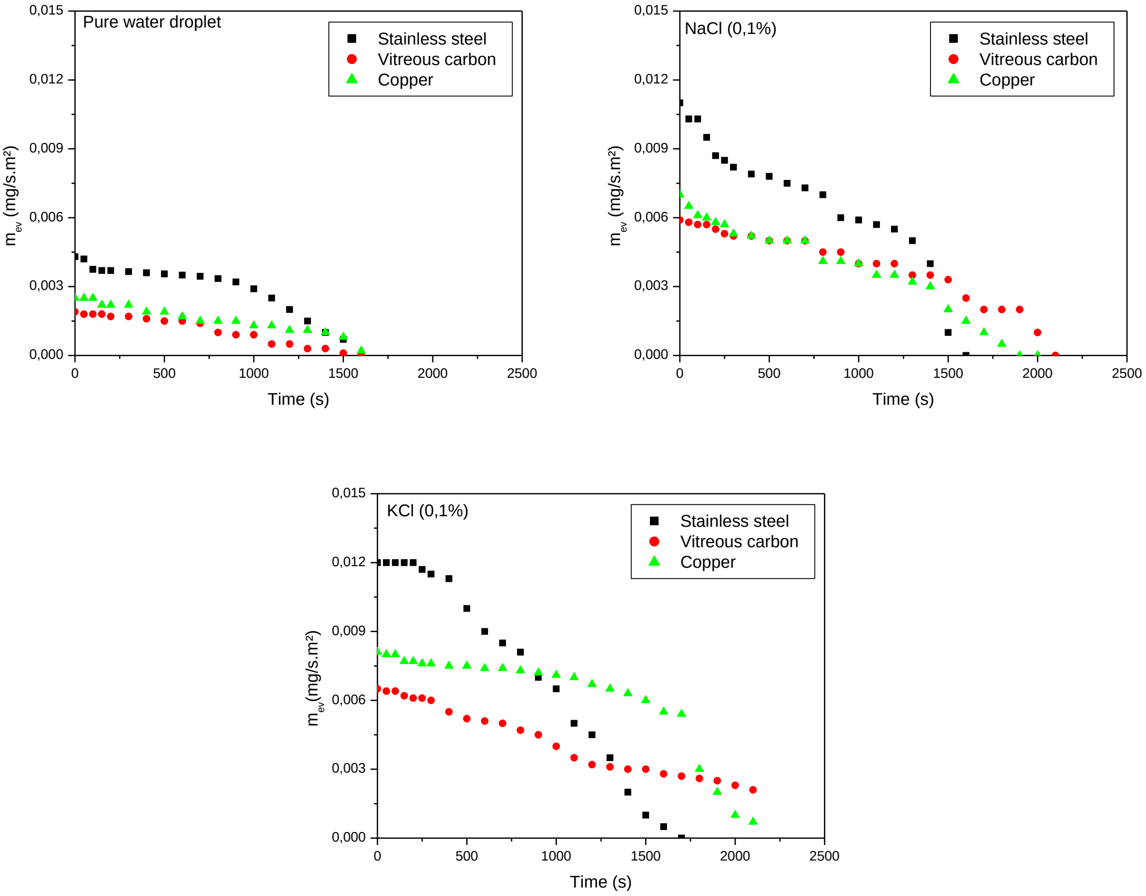


Figure 3: Evaporated flow of salt water (NaCl and KCl) comparing to pure water droplet during its evaporation

Evaporation curves have the same features. It has two phases: a fast phase and slow decaying phase decay. Salt water content greater than 98% evaporates due to the free water content. This is the case of NaCl and KCl. This explains the rapid increase in the weight of droplet. When the water content is between 50-60%, the sample no longer contains free water in its cavities. The remaining material is then considered saturated with bound water, which takes longer to evaporate. Therefore, there is a slow decay of the curve until stabilization. This can justify the decrease of evaporated mass flow as function of time.

The mass decreases differently from a substrate to another. Comparing salt water and pure water evaporation, evaporated flow rate is higher for salt water than pure water droplet for the same substrate. For stainless steel substrate, the maximum evaporated flow rate is about 0,012mg/s.m² comparing to pure water evaporated flow rate which is about 0,004mg/s.m².

The variation of diameter of the droplet as function of time is presented in figure 4.

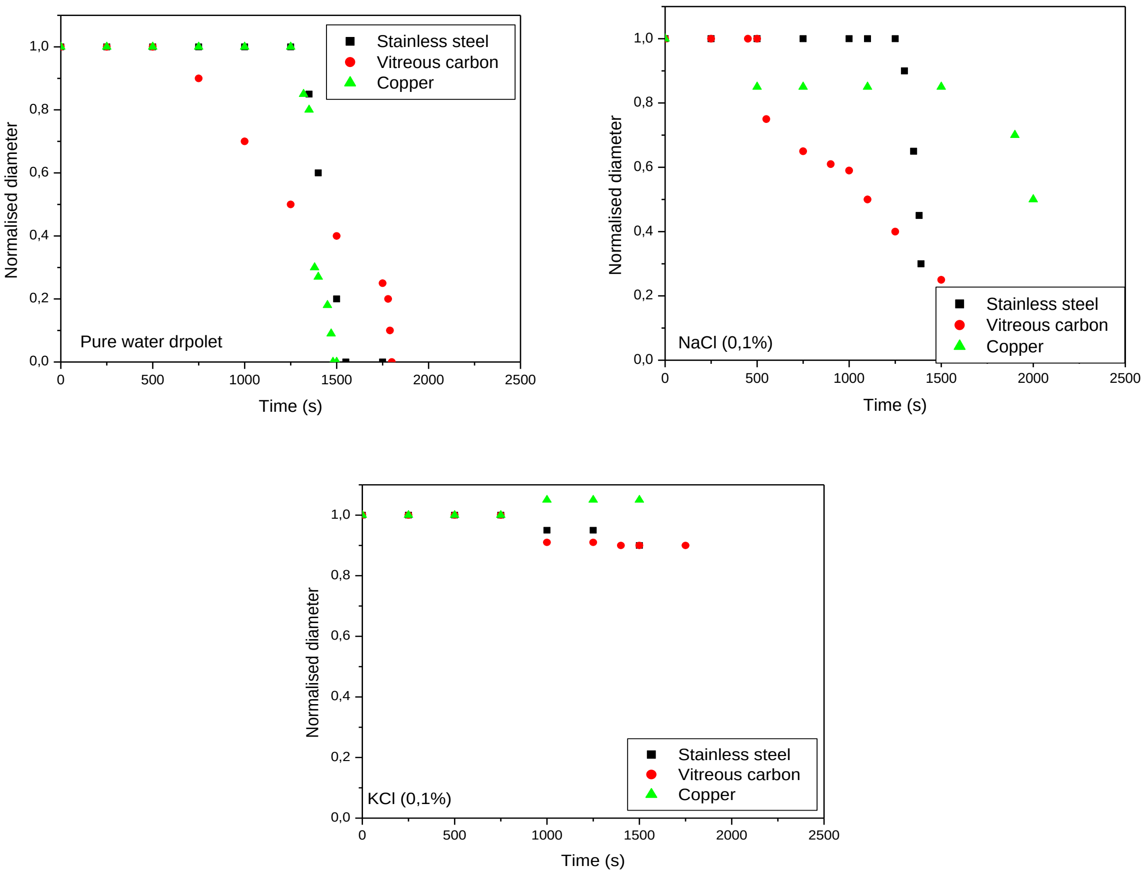


Figure 4: Normalized droplet diameter variation of salt and pure water droplet

Droplet diameter decreases during droplet evaporation process for different substrates and for each liquid. It's seen that the decrease of the diameter is different from a substrate to another but the same shape is observed.

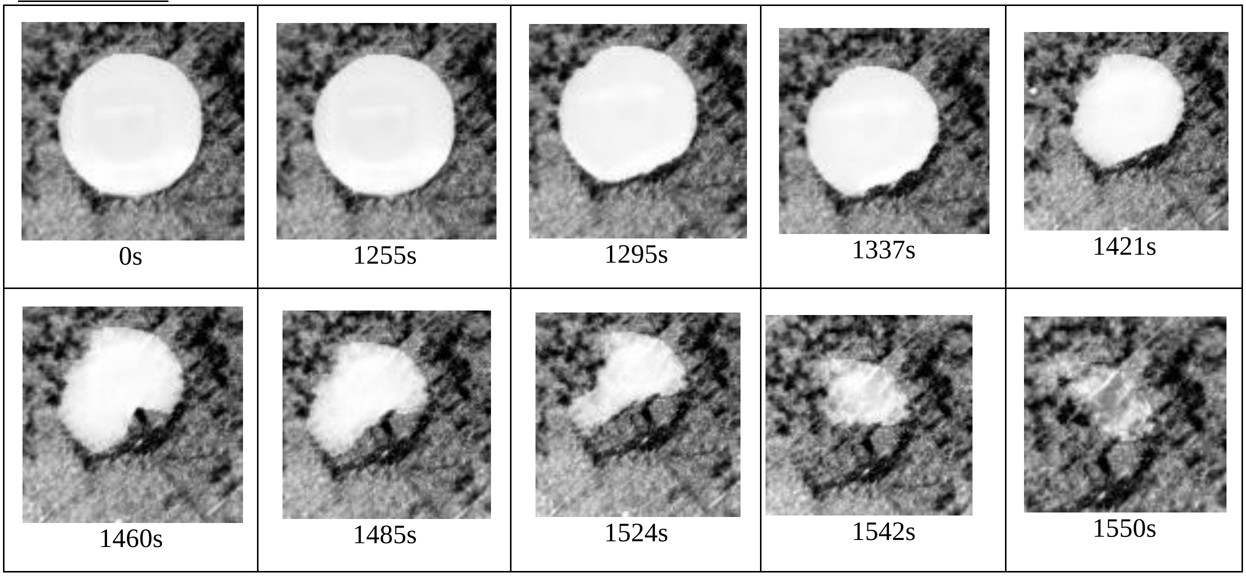
Many phenomena are observed. The diameter remains constant in the first part of the evaporation process. It decreases after a period of time which is different from a substrate to another. Or, the diameter may decrease from the beginning of evaporation process. For KCl droplet, an overflow is observed.

The evolution of droplet diameter can be observed from IR camera video. It's presented in figure 5.

The evolution of pure water droplet diameter during evaporation process indicates that it remains constant until 1255s. From 1295s, the droplet disappearing begins. It's observed that the retraction of the droplet isn't symmetric. It's related to the nature of substrate which isn't homogeneous as Grandas *et al.*, [7] concludes and other studies. When evaporation tests are repeated for the same case, the droplet retraction isn't the same.

Many works, such as Grandas *et al.*, [7] studies the evolution of contact angle during evaporation process to explain the evolution of droplet evaporation until it disappears. This study is focalized on the initial contact angle for the different substrates.

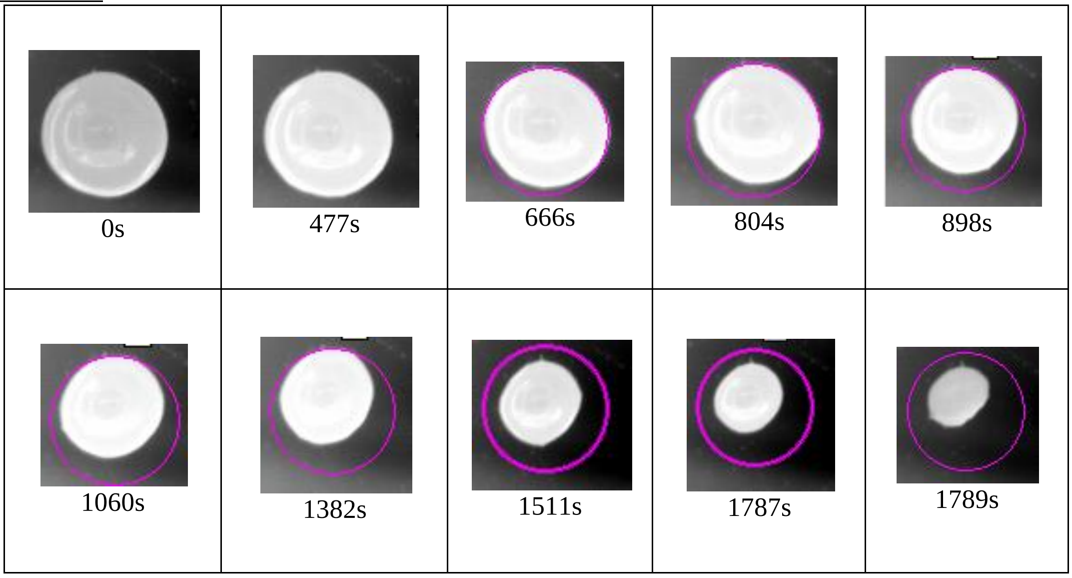
Stainless steel



0s 1255s 1295s 1337s 1421s

1460s 1485s 1524s 1542s 1550s

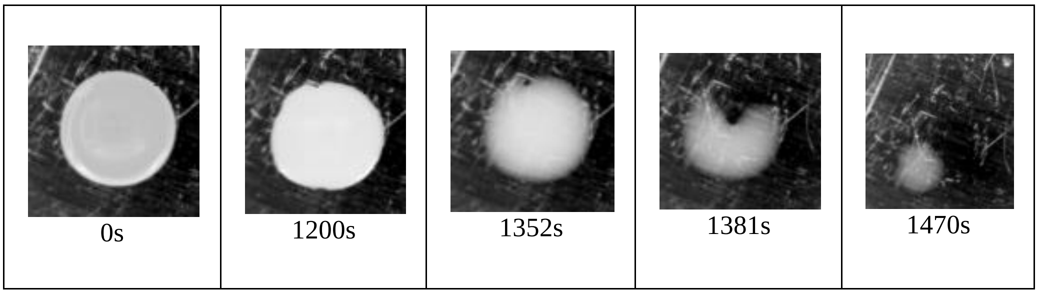
Vitreous carbon



0s 477s 666s 804s 898s

1060s 1382s 1511s 1787s 1789s

Copper



0s 1200s 1352s 1381s 1470s

Figure 5: Infrared camera of the pure water droplet during its evaporation

Table 2: Left and right contact angle for a pure water droplet

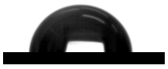
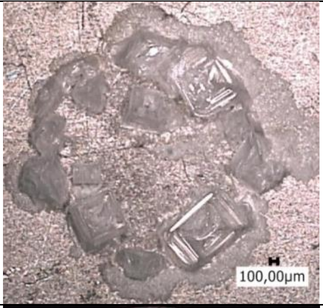
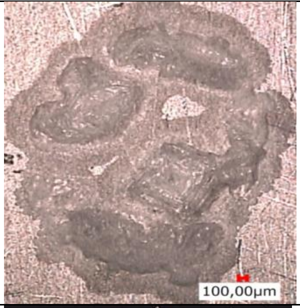
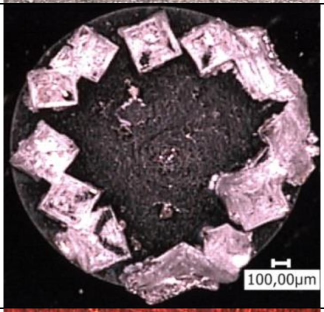
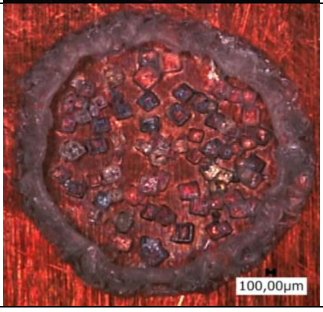
Substrate	Pure water droplet	Contact angle		
		Pure water	NaCl (0,1%)	KCl (0,1%)
Stainless steel		93,37	82,69	85,67
Vitreous carbon		79,09	83,97	91,60
Copper		98,46	90,80	88,95

Table 2 indicates that geometric characterization of the droplet, at ambient temperature, is different to a substrate to another and from a liquid to another. It’s seen that the droplet has different contact angle from a substrate to another and for each salt.

For such substrates, comparing between salt water and the pure water droplet, the contact angle is higher for pure water.

After evaporation, salt water droplet leaves a salt deposit. This deposit has different from a substrate to another and for each salt. The photos of the NaCl and KCl deposit are presented in Table 3.

Table 3: NaCl and KCl droplet deposit

Substrate	NaCl droplet	KCl droplet
Stainless steel		
Vitreous carbon		
Copper		

After evaporation, a NaCl droplet posed on a stainless steel substrate takes the form presented in Table 3. NaCl crystals are contoured with fine particles of salt surrounding each crystal. Crystals of smaller size exist inside the drop.

Fontana *et al.*, [11] worked on the evaporation of a thin layer or a droplet of NaCl and the formation of crystals.

After evaporation, a NaCl crystal takes the form of Figure 6. with stepped and intensified squares with rectangular faces. Fontana’s study indicates that in microgravity when at least one face attached to the free surface, NaCl crystals grow with this tabular square-plate geometry and due to high saturation.

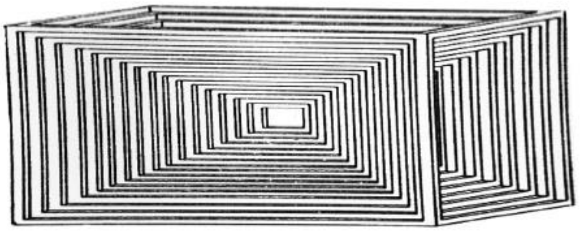


Figure 6: Model of a crystal having a tubular form [11]

The observed crystals, in this case, have the same shape as Fontana *et al*,. A sessile droplet is a droplet posed on a solid substrate, where the wetted surface is bounded by a contact line. The shape of the droplet deposits is controlled by the interaction of the surface tension, wetting angle, gravity the force al, and the geometry of the substrate [12].

For a NaCl droplet, large crystals are formed on the perimeter of the drop, when it's posed on vitreous carbon. Fines crystals exist inside the droplet. The same crystals shape is found by Fontana *et al.,* [11]. It has a form of pyramid hopper which is a particular characteristic form of NaCl.

The NaCl droplet posed on a copper substrate indicates the presence of salt around the droplet and several fine crystals distributed inside it.

The formation of crystals inside the droplet, according to Shahidzadeh *et al.,* [13] is because of the fast decrease of salt concentration. They also consider that the crystal growth of constant super-saturation is linear over time. The growth of the crystal is slow therefore implies that it consumes ions of the solution, super-saturation therefore decreases.

A KCl droplet posed on a stainless steel substrate indicates the presence of crystals having a tubular form. Fine particles of salt extend to increase the radius by 10%. The slight distance of the droplet diameter is due to the growth of salt crystals [13, 14].

Contrary to NaCl crystals, the deposition is characterized by the formation of large crystals at the edges of the drop and small crystals inside.

Shahidzadeh *et al.,* [13] explained that the crystals migration from the exterior towards the center is linked to certain forces. Admittedly, as the size of the crystals increases, the crystal becomes confined between the free surface and the solid substrate. The resulting deformation of the liquid/air interface due to this geometric constraint results from the capillary forces making it possible to push the crystal towards the center of the droplet.

Quantitatively, the displacement of the crystal from the edge to the center L(t) can be described by considering that a cubic crystal of the size d(t) corresponds to the angle of fall with a contact angle θ(t) Distance between the edge and the crystal is: $\mathrm{L(t)} = \frac{\mathrm{d(t)}}{\mathrm{to(\theta)}}$ (Figure 7).

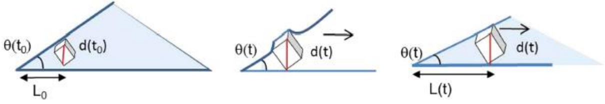


Figure 7: Training and movement of salt crystals to the center of the drop

By measuring independently the contact angle θ (t) and the crystal growth d (t) during evaporation, Shahidzadeh *et al.,* [13, 14] found that θ(t) decreases linearly once the crystallization begins And the size of the crystal itself d(t) is in logarithmic growth over time.

4. Conclusions

This study concerns the study of salt water droplet evaporation. Three substrates are studied for each salt comparing to pure water droplet. The substrates have different physical and thermal properties.

This work is divided into three main parts. The first one is about the variation of evaporated flow rate. This part indicates that the evaporated flow rate is maximum for KCl droplet for all the substrates. For each liquid, the maximum of evaporated flow corresponds to a droplet posed on stainless steel substrate. This can be explained by the initial contact angle which is the minimum for a droplet posed on this substrate.

The second part is about the diameter variation during droplet evaporation. It's seen that the droplet has different. The diameter may remain constant in the first part of the evaporation process. It decreases after a period of time which is different from a substrate to another. This is the case of NaCl droplet posed a stainless steel substrate. Or, the diameter may decrease from the beginning of evaporation process. For KCl droplet, an overflow is observed.

After evaporation, and to summarize the droplets deposits of NaCl and KCl, and for a droplet placed on a stainless steel substrate, a slight overflow of the diameter is observed. For a vitreous carbon substrate, small crystals in the inner part of the NaCl droplet are observed. Larger crystals are present on its contour. However, the inverse phenomenon is observed for the KCl droplet. For a copper substrate, the deposits are different. We find that the shape of the deposition of the drop depends not only on the type of substrate on which the drop is placed but also on other parameters such as the type of salts and the surface forces interacting during evaporation. A MARANGONI calculation is necessary to understand the salt particle movement.

Nomenclature

Symbol	
Cp	calorific capacity
IR	Infrared
k	thermal conductivity, *W/m.K*
KCl	Potassium Chloride
L	displacement of the crystal from the edge to the center
m	mass flow, $mg/s.m^2$
NaCl	Sodium Chloride
t	time
d	size of the salt crystal

Greek letters	
ε	Emissivity
ρ	Density, kg/m^3

Subscript	
ev	evaporated

Acknowledgments

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