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Study on the specific dynamic and thermal conditions leading an ice-hole to maintain its ice during Spring or Summer

Etude de la dynamique spécifique et des conditions thermiques qui conduisent un trou à glace à conserver sa glace durant le printemps et l'été.

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KEY WORDS
Phase Change Material, Numerical simulation, Spectral methods, Seasonal outside atmospheric air conditions, Periodic seasonal temperatures.

Abstract The aim of this study is to give a coherent explanation to the natural phenomenon named "ice-hole". Ice presence inside some ground cavities of small depth, during short meteorological unfavourable periods - Spring or Summer – in some European geographical zones of mean altitude (600 - ~ 900m), unsubmitted to very cold temperatures, is reported since a long time. But, up today, it is not well explained because it was not-economy speaking- a real interesting study subject. This "ice-hole" phenomenon is based on the phase changing of which water is the typical model by its vapour, liquid or solid forms. A first approach will be done on basis of experiments yet effected on volumes containing ice and submitted to a continuous heating on their upper surface. Then, on an identical volume, with the same content (ice), 24h periodical sinusoidal regular temperature conditions will be applied on the upper part of this volume. The temperature amplitudes will be function of the mean seasonal values issuing of local meteorological data. In a second step, to have a better approach of the whole conditions leading to the emergence of this phenomenon, we have taken the natural physical and structural data into account and digitalised them. The results obtained from this numerical approach show that a lot of conditions needs to be considered and can lead to the maintain of a part of ice in this type of hole.

MOTS CLES
Matériau à Changement de Phase, Simulation numérique, Méthodes Spectrales, Conditions atmosphériques extérieures saisonnières, Températures saisonnières périodiques.

Résumé Le but de cette étude est de donner une explication cohérente au phénomène naturel appelé « trou de glace ». La présence de glace à l'intérieur de certaines cavités souterraines de faible profondeur, pendant de courtes périodes météorologiques défavorables - printemps ou été - dans certaines zones géographiques européennes d'altitude moyenne (600 - ~ 900m), non soumises à des températures très froides, est signalée depuis longtemps. Mais, aujourd'hui, cela n'est pas bien expliqué car ce n'était pas – du point de vue économique – un sujet d'étude vraiment intéressant. Ce phénomène de « trou de glace » repose sur un changement de phase dont l'eau est le modèle typique par ses formes vapeur, liquide ou solide. Une première approche sera faite sur la base d'expérimentations déjà effectuées sur des volumes contenant de la glace et soumis à un échauffement continu sur leur surface supérieure. Ensuite, sur un volume identique, avec le même contenu (glace), des conditions de température régulières sinusoïdales périodiques 24h seront appliquées sur la partie supérieure de ce volume. Les amplitudes de température seront fonction des valeurs saisonnières moyennes issues des données météorologiques locales. Dans un deuxième temps, pour avoir une meilleure

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approche de l'ensemble des conditions ayant conduit à l'émergence de ce phénomène, nous avons pris en compte les données naturelles, physiques et structurelles, et les avons numérisées. Les résultats obtenus grâce à cette approche numérique montrent que de nombreuses conditions doivent être prises en compte et peuvent conduire au maintien d'une partie de la glace dans ce type de trou.

1. Introduction

Ice-holes are well-known in Europa (France, Swiss, Slovakia, etc.). These phenomena take place at mid-altitudes (600 - ~ 900m) in small mountains. In these amazing holes, ice can be maintained and was observed even during the heater periods of Spring and Summer. They are generally situated inside forest and they were used by the local inhabitants, up to the beginning of the twentieth secular, to preserve their foods. If these ice-holes are well known, they were not really studied and their functioning not well explained. A very small lot of observations were reported [1] [2] and, on these basis, constructions of ice caves were made [3] [4] and regularly used up to the diffusion of the fridges.

Then, in our study we attempt to explain how these ice-holes are functioning.

In the first part of this paper, we will consider some experiments made in Pau University (France) concerning change phase materials and especially on water, the typical example.

A determined volume containing ice was heated on its upper surface with various continuous temperatures. Fusion level and stabilisation time of the process were registered.

We have replaced the continuous heating by a sinusoidal one, with a diary period (24h) and amplitudes issuing of the seasonal meteorological means of the region in which these ice-holes were observed (Massif Central in France). Volume walls are maintained at constant temperature.

In a second step, we have taken the natural physical and environmental conditions, in which the ice-hole is situated, into account and digitalised them. In the same way, we have used meteorological mean temperatures values for the four seasons matching with the regional ones.

Then, from the results obtained it is possible to define the conditions necessary to maintain a significant part of the initial volume of ice in the volume representing an ice-hole.

2. Modelling

2.1. Nomenclature and units

C_P	Heat capacity, $J\ kg^{-1}\ K^{-1}$
D_S	Solid domain (ice), m^3
D_L	Liquid domain (water), m^3
D_W	Whole domain, m^3
g	Gravitational acceleration, $m\ s^{-2}$
GC	Great Cavity above the ice-hole
k	Thermal conductivity, $W\ m^{-1}\ K^{-1}$
La	Latent heat of fusion, $J\ kg^{-1}$
P	Pressure, *Pa*
PCM	Phase Change Material
r	Radial coordinate, *m*
t	Time, *s*
T	Temperature, *K*
T_{air}	Sinusoidal variation of the external air temperature, based on the meteorological mean values, *K*
T_{bot}	GC bottom temperature, *K*
T_{ext}	External air temperature at the ground level above the GC, *K*
T_{max}	Maximal air temperature, *K*
T_L	Liquid part temperature, *K*, with: $T_L \geq 0°C$
T_{mean}	Mean temperature of the ice-hole, *K*
T_S	Solid part temperature, *K*, with: $T_S \leq 0°C$
T_{walls}	Ice-hole side walls temperature, *K*
u	Axial velocity
v	Radial velocity
$\vec{V}$	Velocity field vector: $\vec{V} = (u, v)$
x	Axial coordinate, *m*

Greek symbols

μ	Dynamic viscosity, *Pa s*
ρ	Density, $kg\ m^{-3}$

Subscripts

I	Interface solid domain / liquid domain
L	Liquid domain (water)
S	Solid domain (ice)
W	Whole domain

2.2. Study domain: some definitions

In the ice-hole case, we are in presence of a Phase Change Material (*PCM*): water in the liquid or solid (ice) phases. Some experiments and modelling yet made in the SIAME Laboratory (Pau University, France) were presented at the 2nd International Conference on Thermal Sciences in April 2012 at Casablanca and Agadir (Morocco) [5][6]. They will be the basis of our numerical simulation. Consequently, they will be selected as models for the usual conditions of the ice container volume. The container's walls are insulated and its bottom continuously frozen at – 5°C (Figure 1a).

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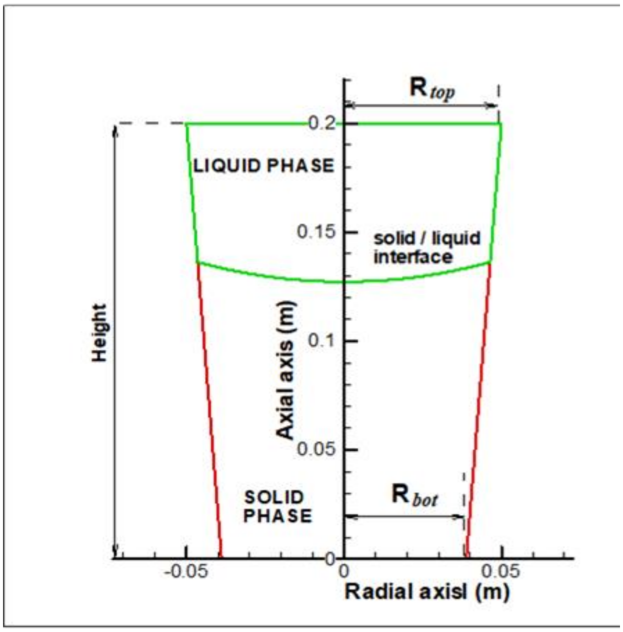

Fig. 1a: the liquid and solid states are represented at an arbitrary moment in the volume considered.

The open-air top of the volume is heated at various continuous temperatures from 10 to 30°C. In the considered configuration, these works have shown that the totality of the ice contained in the volume cannot be melted. When the melting process is stabilized at around 5 to 10 days, depending on the applied temperature values, it remains around 15% of the ice with 30°C heating and more than 40% for 10°C (Figure 1b).

Then the boundary conditions were modified. The continuous heating was replaced by a daily (24h) sinusoidal variation of temperature based on the mean seasonal meteorological values in Pontgibaud (Puy de Dôme, France) [7]. Consequentially our modelling conditions will be defined as it follows:

● The hole form – a truncated cone – was chosen for axial-symmetry reasons.

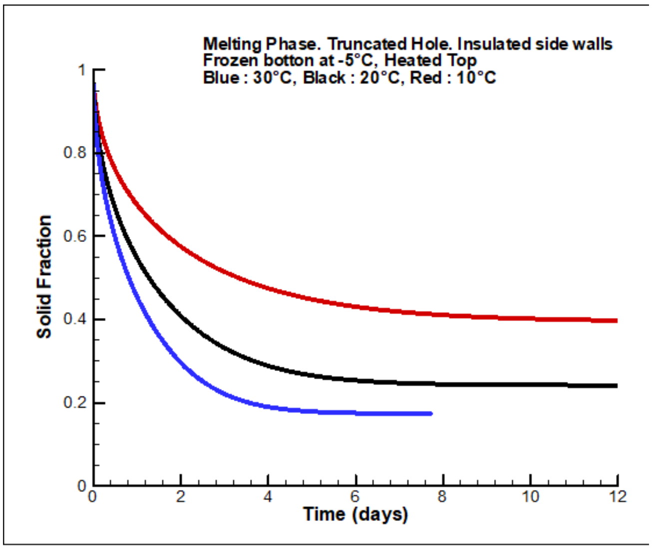

Fig. 1b: daily variation of the ice percentage inside the volume for 3 different types of constant heating.

2.3. Solid and liquid parts

We give below some definitions used in our modelling:

- The whole "ice-hole domain" D_W is defined by: $D_W = D_S \cup D_L$
- The « Solid domain » D_S is the domain in which water is in a solid state with a temperature lower than the melting point. In the following test-case, it corresponds to: $T_S \leq 0°C$

The « Liquid domain » D_L corresponds to the domain in which water is in a liquid state with a temperature higher than the melting point. In the following test-case: $T_L \geq 0°C$

Solid (ice) and liquid (water) parts are defined as it follows:

- $$Solid\ Fraction = \frac{Volume\ of\ D_S}{Total\ volume} \quad (1)$$

and $$Liquid\ Fraction = \frac{Volume\ of\ D_L}{Total\ volume} = 1 - Solid\ Fraction \quad (2)$$

- The mean temperature of the hole T_{mean} is defined as the mean temperature of the whole study domain D_W:
$$T_{mean} = \frac{1}{\langle D_W \rangle} \iint_{D_W} T(r,x)drdx \quad (3)$$

where $\langle D_W \rangle$ represents the area of the domain D_W.

2.4. Seasonal ambient air temperature: "severe Winter", "Winter", "Spring" and "Summer"

The simulated ambient air temperature applied on he open-air surface of the hole is a sinusoidal function with a 24 h daily period, with a maximal value T_{max} at 12 h (noon) and a minimal value T_{min} at 0 h (midnight).

$$T_{air} = \alpha \sin\ (\omega t) + \beta \quad (4)$$

With: $\alpha = \frac{T_{max} - T_{min}}{2}$; $\beta = \frac{Tmax + T_{min}}{2}$ (5)

and: $\omega = \frac{2\pi}{Period}$ $with\!: Period = 86400\ s$ (6)

Some ice-holes are localised in the Pontgibaud region situated at about 19 km of Clermont-Ferrand in the Massif Central (France). As a result, the chosen mean temperature values to define the four types of "meteorological" seasons will be based on the mean temperatures data issuing from the nearest meteorological station, the one of Clermont-Ferrand-Aulnat [8].

Severe Winter or Winter (from December to February); Spring (from Marsh to May); and Summer (from June to August) are defined. The maximal temperature variations for Autumn (from September to November) being included inside the other seasons values will not be presented here.

- Severe Winter, with: T_{max} = 2°C and T_{min} = - 10°C
- Winter, with: $T_{max} = 10°C$ and $T_{min} = -5°C$
- Spring, with: $T_{max} = 16°C$ and $T_{min} = -2°C$
- Summer, with: $T_{max} = 20°C$ and $T_{min} = 5°C$

2.5. Standing forced temperatures on the substratum containing the ice-hole

Without any known experimental data, however is the season, the bottom and the side walls of the volume (truncated cone hole) are submitted to 2 types of temperature:

1) In the hypothetic case of a permanently frozen soil

- Side walls: $T_{walls} = -2°C$ and bottom $T_{bot} = -5°C$:

This value of – 5°C is the one of the original ice-block assumed to be initially present in the volume.

2) In the hypothetic case of a permanently unfrozen soil

- Side walls: $T_{walls} = 5°C$ and bottom: $T_{bot} = 2°C$

2.6. Equations governing the PCM melting

The ice-hole described above is a two-dimensional axisymmetric section of a straight **truncated cone.**

In these conditions, at each time t > 0, the equations governing the PCM melting are related to two phases:

- **Solid Phase:** this phase is described by the diffusion equation:

$$\rho_S C_{P_S}\left(\frac{\partial T_S}{\partial t} + \vec{V} \cdot \vec{\nabla} T_S\right) = k_S \Delta T_S \quad (7)$$

- **Liquid Phase**: The temperature differences are assumed sufficiently low to justify the Boussinesq approximation. The fluid (water) is assumed to be Newtonian and isotropic, and the flow is laminar and incompressible. Then, our problem is described by Navier-Stokes (movement quantity and continuity) and Energy equations.

Their classical vector formulation is as follows:

$$\rho_L C_{P_L}\left(\frac{\partial \vec{V}}{\partial t} + (\vec{V} \cdot \vec{\nabla})\vec{V}\right) = -\vec{\nabla} P + \mu_L \vec{\nabla}.\left(\nabla \vec{V} + \nabla^t \vec{V}\right) + \rho_L \vec{g} \quad (8)$$

$$\vec{\nabla}.\vec{V} = 0 \quad (9)$$

$$\rho_L C_{P_L}\left(\frac{\partial T_L}{\partial t} + \vec{V} \cdot \vec{\nabla} T_L\right) = k_L \Delta T_L \quad (10)$$

- **Interface Solid/Liquid**: The time-evolution of the interface height $H_I(r,t)$ is given by:

$$\rho_S L_a \frac{\partial H_I}{\partial t} = \alpha_I \left[1 + \left(\frac{\partial H_I}{\partial r}\right)^2\right] \quad (11)$$

where α_1 traduces the heat transfer between the solid and liquid phases along the interface:

$$\alpha_I = k_L \left(\frac{\partial T_L}{\partial r}\right)_I - k_S \left(\frac{\partial T_S}{\partial r}\right)_I \quad (12)$$

2.7. Boundary conditions

Whatever the studied case, the imposed conditions at the boundaries limits of the studied domain are, at each moment *t*>0**,** the ones defined by the soil nature and the temperature amplitude variations for the chosen season.

- For the upper part of the volume, directly in contact with the external air: *T* = T_{air} as defined for each "season";

- For the side walls of the hole, we consider thermal exchanges with a relatively small exchange coefficient
- For the bottom, a standing temperature *T* = T_{bot} depending on the soil conditions.

- For the sake of simplification, the hole is considered as axisymmetric and the side walls as waterproof; that is the case in the natural conditions for the hole sides in contact with ice.

2.8. Initial starting conditions (t = 0): ice block, at 6h am

This study deals with the determination of the atmospheric temperatures allowing to maintain ice presence (solid part) in a ground cavity whatever the season.

We start always with a steady state regime, under the hypothesis of an initial presence of an ice block occupying the totality of the hole volume, at the temperature of – 5°C.

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The water level in this volume will result solely of the melting of this ice block submitted to the external temperature variations. In the case of complete melting of this ice block, the volume occupied by water will be lower than the ice one inside the hole. Nevertheless, this residual volume will be neglected. We recall that: ice density = 0.917 kg / dm^3 and water density = 1kg / dm^3.

In the nature, the ice-holes have a preponderant orientation to the North and they have a small open-air surface. We have taken these conditions into account but we have neglected the evaporation effect very depending of the temperature at the upper surface of the ice-hole. It is the same for a possible providing by rain water or condensation process inside the remaining air volume resulting from the melting above the ice block.

Firstly, we will comment the results obtained in the case of an ice-hole with an open-air surface at the ground level, for frozen soil conditions (Side walls: T_{walls} = - 2°C and bottom: T_{bot} = - 5°C) submitted to 4 "seasons" conditions.

2.9. Summary Procedure for Numerical Resolution

For the numerical resolution, the method used is based on references contained in [9].
We recall the main steps below.
The PCM melting equations (7)-(12) are written in axisymmetric vorticity - stream function formulation (ω, ψ), which is finally reduced to ψ-formulation after elimination of the vorticity ω, as follows:

$$\frac{\partial \omega}{\partial t} - \frac{1}{r}\frac{\partial \psi}{\partial x}\frac{\partial \omega}{\partial r} + \frac{1}{r}\frac{\partial \psi}{\partial r}\frac{\partial \omega}{\partial x} + \frac{1}{r^2}\frac{\partial \psi}{\partial x}\omega = \frac{\mu}{\rho}\left(\frac{\partial^2 \omega}{\partial x^2} + \frac{\partial^2 \omega}{\partial r^2} + \frac{1}{r}\frac{\partial \omega}{\partial r} - \frac{\omega}{r^2}\right) - g\beta\frac{\partial T}{\partial x} \quad (13)$$

where:

$$\omega = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial r} = -\frac{1}{r}\left(\frac{\partial^2 \psi}{\partial x^2} + \frac{\partial^2 \psi}{\partial r^2} - \frac{1}{r}\frac{\partial \psi}{\partial r}\right) \quad (14)$$

The obtained equations are solved by high accuracy numerical approximation, the spectral-collocation methods [9], using the bijective Landau operators [9] to transform each primary domain (r, x) into a square domain $(\tilde{r}, \tilde{x})$.

The stream function Ψ (or the temperature T) is projected on suitable $(N_r + 1) \times (N_x + 1)$ trial functions $P_l(\tilde{r})$ and $Q_k(\tilde{x})$, linear combination of Chebyshev polynomials [9], as follows:

$$\psi(r, x, t) = \sum_{k=0}^{N_x}\sum_{l=0}^{N_r} \alpha_{kl}(t) P_l(\tilde{r}) Q_k(\tilde{x}) \quad (15)$$

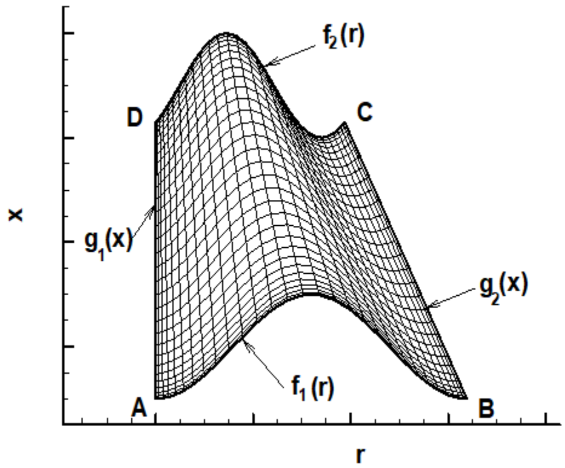

Fig. 2a

Landau Transformation

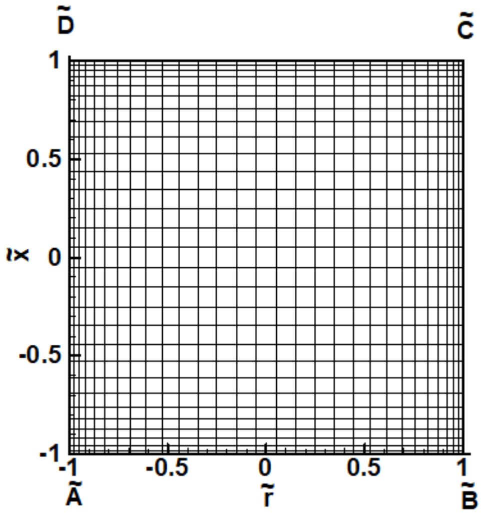

Fig. 2b

Fig. 2a: Example of 32 x 32 collocation points after Landau-Transformation on a study domain defined by 4 functions.

Fig. 2b: Corresponding collocation points on the square of reference $[-1, 1] \times [-1, 1]$.

In each study domain ABCD (solid domain or liquid domain), described by 4 functions as shown in the general figures (fig.2 a and fig. 2b), we discretize the obtained spectral system by using Gauss-Lobatto collocation points [9] defined on the square of reference $[-1,1] \times [-1,1]$ by:

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$$\left(\tilde{r}_j, \tilde{x}_i\right)_{\substack{0\le i\le N_x \\ 0\le j\le N_r}} \quad (16)$$

with: $\tilde{x}_i = -cos(i\pi/N_x)$ and: $\tilde{r}_j = -cos(j\pi/N_r)$ (17)

Finally, the discretized nonlinear equations obtained are linearized by Newton method and Crank-Nicolson Scheme [9] is used last to perform time-integration.

3. Results obtained in the case of a standing frozen soil (bottom temperature = - 5°C)

3.1. Summary of the results obtained for the four seasons

For the sake of simplicity, we give below only a brief summary of the results obtained without presenting the corresponding figures.

3.1.1 Severe Winter: ambient air temperature amplitude ($T_{max} = +2°C; T_{min} = -10°C$)

● The mean temperature of the hole is negative, almost constant, and equal to – 2°C.

● The solid part (ice) is nearly equal to 100% when liquid part is quasi null with a maximal value of about 3%.

● The maximal solid part is centred on the minimal temperature value and its duration is around 16h 30 min.

● The maximal melting point is about 1h delayed by comparison with the maximal external air temperature value (+ 2°C).

3.1.2. Winter: ambient air temperature amplitude ($T_{max} = +16°C; T_{min}$ = - 2°C)

● The mean temperature of the hole is negative, oscillating between – 1°C and - 2.3°C

● The solid part (ice) is varying between 83% and 100%. The liquid part (water) does not exceed 17%.

● The period during which the water level due to melting is null is centred on the minimal value of the temperature signal (- 5°C). Its duration is of the order of 9h 15mn.

● The melting maximal value is delayed of about 3h 40mn by comparison with the maximal external air temperature (+ 10°C).

3.1.3. Spring: ambient air temperature amplitude ($T_{max} = +16°C; T_{min}$ = - 2°C)

● The mean temperature of the hole is around the fusion point, oscillating between + 1.3°C and – 1.8°C

● The solid part (ice) is varying between about 65% and 98%, as a function of the sinusoidal 24h external temperature duration.

● When the external air temperature is around its minimal value (- 2°C) there is no more water inside the hole during about 6h.

● The ice quantity is decreasing regularly in relation with the increasing mean temperature value of the hole before to be stabilized after 6 to 9 days. The liquid part (water) does not trespass 35%.

● The maximal melting value is delayed of about 6h by comparing with the maximal external air temperature (+ 16°C).

● Starting in phase, an increasing delay takes place, up to 2 hours, between the external temperature and the hole mean temperature. Then, in about 7 days, this delayed synchromism is stabilized.

3.1.4. Summer: ambient air temperature amplitude ($T_{max} = +20°C; T_{min}$ = + 5°C)

● The mean temperature of the hole is very low for the season and contained in the + 0.3 to + 3.7°C values even if the mean external temperature is about + 12.5°C

● The solid part (ice) is a decreasing in time function reaching a 50% minimal value stabilized in about 6-9 days. The complementary liquid part (water), in the same time, evolves in an opposite way and does not trespass 50%.

This study is dealing with the determination of the meteorological conditions leading to the possible maintenance of ice inside a ground cavity as a function of seasons, and, consequently of the mean temperature of this cavity named ice-hole.

For simplifying reasons, we will present only, in the following Figures 3, 4, 6 and 7, the curves obtained for two seasons.

Severe Winter, being more favourable than Winter, and Summer, normally unfavourable for the ice maintenance, only Winter and Summer will be presented. That permits to show the wrapping bounds of the ice maintenance inside the cavity.

3.2. Comparisons between two imposed seasonal conditions in the case of a frozen soil ($T_{bot} = -5°C$)

On the following **Figure 3** are reported, for the Summer and Winter seasons, the mean temperatures inside the ice-hole (dotted lines) and the corresponding evolution time of the solid part (ice) (continuous lines).

During Winter, warmer than severe Winter, the inside mean temperature of the hole is always lower than the melting point. Consequently, the ice quantity is always higher than 80% of the initial volume even during the warmer hours of the day ($T_{max} = +10°C$).

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During Summer, the inside mean temperature of the hole is increasing always to a positive value, stabilized around + 1.8°C and leads to a regular decreasing quantity downing around 50% in about 6 – 9 days.

Logically, the evolution of the solid part (ice) quantity inside the ground cavity is in the foreseen way: colder the season is, more the ice quantity is important. Warmer the season is, lower is the ice quantity inside the ice-hole.

It can be noticed that, as in the continuous heating process (Figure 1b), a stabilisation time, of around 6-9 days, depending on the applied temperature, is needed as it appears in Summer.

With a regular amplitude variation of temperature, whatever the season, it remains always an important solid part > 50% in the ice-hole.

This could be due to the temperature of the bottom hole standing at a temperature lower than – 5°C.

Liquid part (water) occupies the remaining volume.

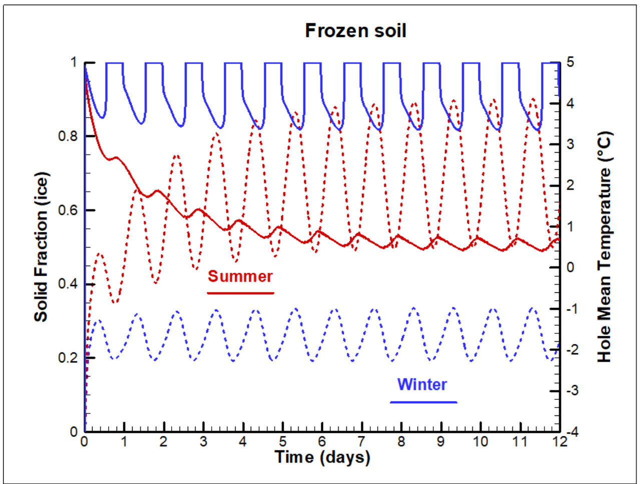

Fig. 3: Daily variations of the mean temperature (dashed lines) and of the ice percentage (continuous lines) inside the ice-hole, for the two seasons considered.

4. Results obtained in the case of a standing unfrozen soil (bottom temperature = + 2°C)

Only the bottom hole temperature was modified from – 5°C to + 2°C. Then the ratio between the solid part (ice) and the liquid part (water) in the ground cavity could be changed in relation with the imposed "season" temperatures.

Unlike the frozen ground conditions, the melting phenomenon will take place not only on the upper open-air ice-hole surface but also between the ice block, at – 5°C, and the side walls at + 5°C and the bottom at + 2°C.

4.1. Summary of the results obtained for the four seasons

For similar reasons to the case of a frozen soil, we give below only a brief summary of the results obtained without presenting the corresponding figures.

4.1.1. Severe Winter: ambient air temperature amplitude (T_{max} = + 2°C; T_{min} = - 10°C)

- The mean temperature of the hole is almost constant, slightly positive, and about to + 0.8°C
- The solid part (ice) is nearly equal to 30 - 35% when liquid part is occupying the remaining volume
- The minimal solid part is centred on the maximal external temperature value (+ 2°C). On the other hand, the maximal solid part is delayed of about 5h 40mn by comparing with the minimal external air value and remains about constant all along the half negative period.

4.1.2. Winter: ambient air temperature amplitude (T_{max} = + 10°C; T_{min} = - 5°C)

- The mean temperature of the hole is positive, around + 1°C) oscillating between – 1°C and + 3.5°C
- The solid part (ice) is unregularly oscillating varying between 7% and 97% during very short times, of the same mean order than the one during severe Winter. The liquid part is varying in an opposite way.
- The minimal value of the solid part is delayed of about 6 hours by comparing with the maximal external temperature value (+ 10°C). On the other hand, the maximal solid part value is delayed of about 3h 30mn by comparison with the minimal external air temperature (- 5°C).
- There is an accordance in phase starting for the external air and mean temperature of the hole followed by an increasing delay up to 2 hours the 6th day after which it is stabilized. Nevertheless, the melting maximal value is delayed of about 10 hours by comparison with the maximal external air temperature (+ 10°C).

4.1.3. Spring: ambient air temperature amplitude (T_{max} = + 16°C; T_{min} = - 2°C)

- The mean temperature of the hole is always positive. It increases regurly and stabilizes in about 6-9 days, oscillating between + 1.5°C and + 6.5°C
- Before to be stabilized, after the 6th day, there is an oscillations time during 5 days, in which the amplitude variations of the solid part are comprised between 75 to 10%.
- Then, regularly decreasing, this solid part oscillates from 22% down to about 3%.

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- The maximal solid part obtained is delayed of about 1 hour compared to the minimal external air temperature (-2°C)

Apparently, it results that it remains always a small solid part inside the ice-hole even when the external air temperature reaches its higher value.

4. 1.4. Summer: ambient air temperature amplitude (T_{max} = + 20°C; T_{min} = + 5°C)

- The mean temperature of the hole is always positive. It is periodical, increasing during 5 days before to be and regularly oscillating between 5.3 and 9.3°C.

- In the same time the solid part decreases very rapidly down to 2-3% the 6th day. At this moment, the minimal mean temperature of the hole is delayed of about 3h 30mn in comparison with the minimal external air temperature. As for the previous case, similar shifting phase phenomena can be noted between the maximal external air temperature, the maximal mean temperature of the hole and the minimal solid part.

This is due to the sharing in time in the hole volume of the solid (ice) and liquid (water) parts and to the differences between their thermal inertia. Then it appears that, in these conditions, it could not rest a significant solid part inside the hole if the external temperatures are maintained in our regular hypothetical values.

4.2. Comparisons between two imposed seasonal conditions in the case of an unfrozen soil $T_{bot} = +2°C$

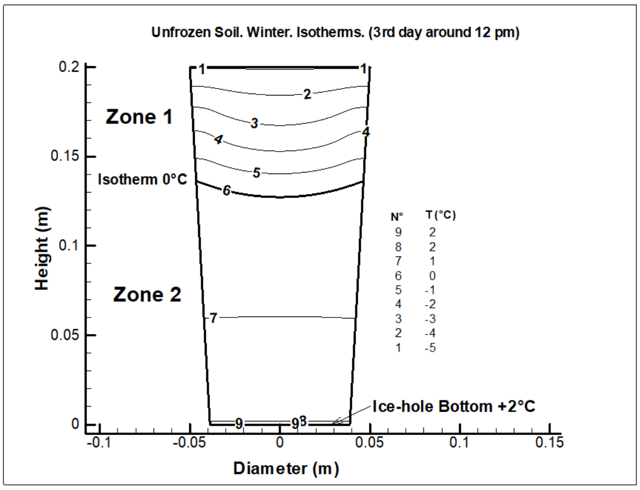

Figure 4: Daily variations of the mean temperature (dashed lines) and of the ice percentage (continuous lines) inside the ice-hole, for the two seasons considered.

Figure 4 shows the behaviour differences, in function of time, between the two more significant seasons – Winter (blue lines) and Summer (red lines) – of the mean temperatures inside the ice-hole (dotted lines) and the corresponding solid part (ice) (continuous line).

The phase shifting between the minimal temperatures and the maximal solid part appears clearly.

Figure 5 permits to explain the numerical oscillations which can be seen **in Figure 4** during Winter, and which were yet registered in Spring,

In fact, the numerical oscillations are due to the simultaneous presence inside the hole of the two solid and liquid parts, sharing the space into the volume, and which have very different thermal characteristics: inertia and conductivity.

Consequently, the volume occupied by each part, at each moment, will be acting on the mean hole temperature acting in its turn on the melting process and the position of the isotherm 0°C (level N°6 in figure 5).

This results in an apparent oscillating process.

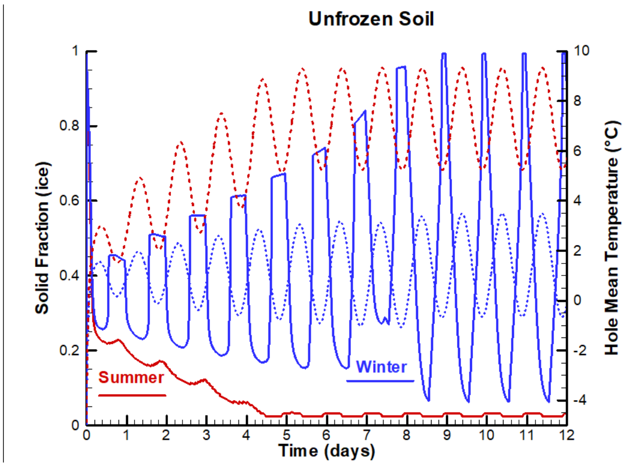

Fig. 5: Example of the isotherm stratification inside the ice-hole, the 3rd day around 12 pm (0h), during winter

5. Comparisons between the different seasonal and thermal conditions imposed to the considered volume

In a first step we will compare the link between the mean temperature hole and the variations of the solid parts for the two seasons (Winter and Summer) in the two thermal hypothesis: frozen ($T_{bot} = -5°C$) or unfrozen ($T_{bot} = +2°C$) soil.

At first, it must be noted that for the sever Winter seasonal conditions ($T_{max} = +2°C; T_{min} = -10°C$), the quantity of solid part can be strongly modified, varying from more than 95% in frozen soil to about 30-35% in unfrozen one.

5.1. Winter: ambient air temperature amplitude ($T_{max} = +10°C$ and $T_{min} = -5°C$)

- In frozen soil, (black lines **in Figure 6**) the minimal solid part (ice) is equal to 85% at its minimum.

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- In unfrozen soil (red lines in **Figure 6**), after 8 days, during with a periodic regime takes place, there is always an ice residual quantity of about 5% alternating regularly with 98% during very short durations.
- In unfrozen soil, the water solid part (ice) could reach a quasi-null value.

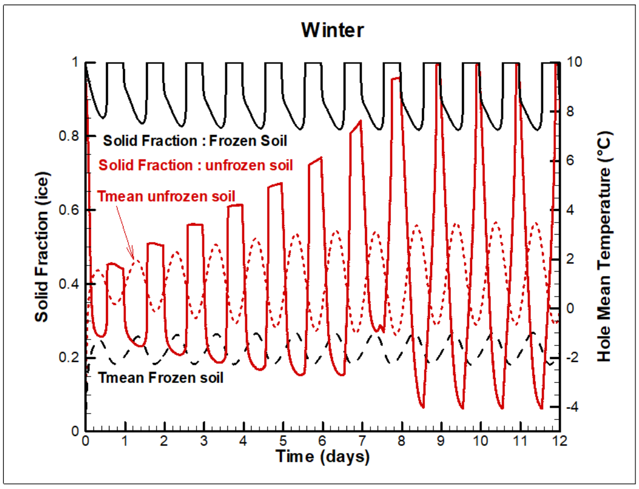

Fig. 6: Daily variations, during Winter, for the two soil conditions considered (Frozen in black lines or unfrozen in red lines) of the mean temperature (dashed lines) and of the ice percentage or solid fraction (continuous lines) inside the ice-hole.

Then it appears clearly that, by taking the hole mean temperature into account the external air temperature and, equally, the temperatures surrounding the hole as a function of seasons, plays the more important role for the presence of ice.

As it can be seen, higher are the mean temperature of the ice-hole and its amplitude variation, higher are the instabilities and reduced the duration of the ice level inside this ice-hole.

5.2 Summer: ambient air temperature amplitude ($T_{max} = +20°C$ and $T_{min} = +5°C$)

- In frozen soil (black lines), following a slowly decreasing ice quantity period of about 7 – 8 days, the process is stabilized and the solid part is around 50 – 55% in volume.
- In unfrozen soil (red lines), the solid part (ice) could – in the same time of 6-8 days - reach a quasi-null value, and the hole volume would be water full.

The Figure 7 shows clearly the temperature evolutions (dotted lines) and the resulting ice variation as a function of time. The process initiated in Spring is amplified in Summer.

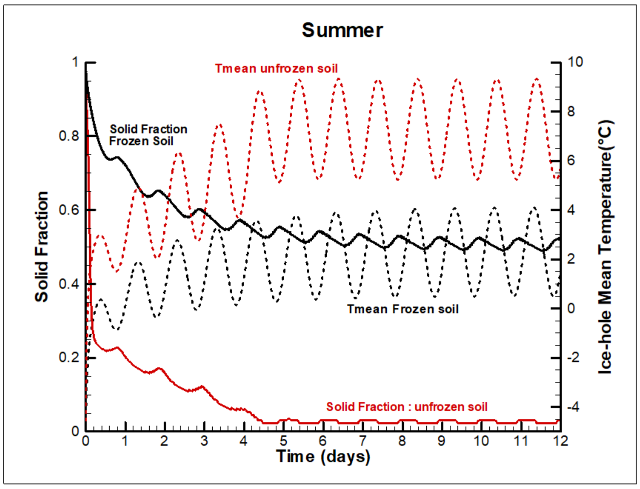

Fig. 7: Daily variations, during Summer, for the two soil conditions considered (Frozen in black lines or unfrozen in red lines) of the mean temperature (dashed lines) and of the ice percentage or solid fraction (continuous lines) inside the ice-hole.

We can note the increasing delayed phase between temperature and ice part in the first 6 – 8 days, depending on the soil characteristics, followed by stabilisation in the succeeding days.

Then, temperature of the bottom and of the hole side walls plays a main role, by determining the

share of the solid (ice) and liquid (water) phases volumes inside the cavity.
These two phases, by their thermal characteristics, act on the mean temperature value of the hole determining then the ice formation and/or its maintenance.

5.3. Dephasing behaviour comparisons between frozen and unfrozen soils

Dephasings as a function of the seasonal temperatures are measured during the permanent regime stabilized generally from the 6th or 8th day.

Calculations are numerically done by comparing the maximal external air values (T_{ext}) with the hole mean temperature ones (T_{mean}) and the minimal solid part in the considered volume.

These dephasings represent the needed time necessary to move from the solid to the liquid phase in relation with the external applied temperature.

5.3.1. In a frozen soil, with the hole side walls at + 2°C and bottom at – 5°C:

In relation with the imposed hypothetical initial conditions, due to the lack of experimental data, we notice a phase delay like an hour, quasi constant remaining, between the ambient air temperature (T_{ext}) and the hole mean one (T_{mean}) from Winter to Summer.

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This late is continuously increasing from 4 hours in Winter up to 7h 45mn in Summer between the ambient air temperature (T_{ext}) from the maximal solid part (ice) volume.

In the severe Winter conditions (T_{ext} from + 2°C to - 10°C) the external temperatures imposed are colder than the side walls and bottom ones. It results that the solid part is always practically at its maximal value when the liquid part does not exceed 3%. In these conditions the amplitude variations of temperatures are too low to permit significant phase delays with the external temperature. These functions can be considered as constant in a periodical system and the hole mean temperature gap about 0.1%.

5.3.2. In an unfrozen soil, with the hole side walls at + 5°C and bottom at + 2°C

The phase delaying is about 3 hours, quasi constant remaining, between the ambient air temperature (T_{ext}) and the hole mean one (T_{mean}) from Winter to Summer.

This delay is verified by the constant gap separating the curves showing the delay evolution between the ambient air temperature (T_{ext}) and the hole mean one (T_{mean}) to the maximal ice volume, from Winter to Summer.

This late is continuously increasing from 7 hours in Winter up to 15h in Summer between the ambient air temperature (T_{ext}) from the maximal solid part (ice) volume.

This constant increase (**Figure 8**) between the minimal external temperature and the hole-mean one, is related to the ice remaining or produced inside the volume. This evolution is also linked to the sharing of the liquid and solid parts inside the hole volume in function of the various temperatures on the side walls. This can be imputed to the differences in the thermal characteristic of ice and water.

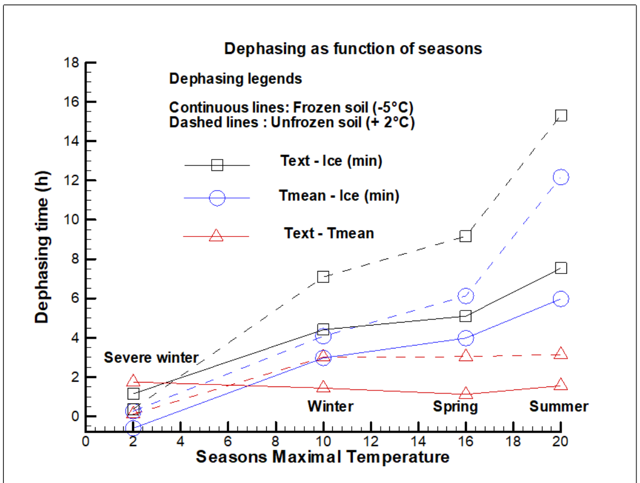

Fig. 8: dephasing between the maximal various temperatures and the minimal percentage of ice for the four seasons

For a "normal" Winter it remains always an about 55% of ice because the mean temperature inside the hole is quasi constant around 1.5°C.

But, in Summer, quantity of solid part (ice) could be reduced to a quasi-null value in only 5 days as it can be seen on **Figure 7**.

In the two considered cases, frozen or unfrozen soil, dephasing is increasing in relation with the rise of the external temperature from severe Winter to Summer. But, for a pair of variables, the delay is always higher for an unfrozen soil than for a frozen soil.

That points out the importance of the soil temperatures in which the ice-hole is situated.

Nevertheless, the natural conditions in which some ice-holes can be observed show that, the more generally, these holes are found at the bottom of the cavity, which can reach some meters deep. Then it is necessary to determine its influence on the "heating" conditions of the upper side, the open-air surface, of the ice-hole.

This cavity will be named "Big Air tanker" or Great cavity" (GC).

6. Simulation by taking a Great Cavity (GC) above the ice-hole into account

There is a very small quantity of descriptions and experimental data on the ice-holes phenomenon. We will recall French papers we possess, making reports on the mountainous Massif Central region (France).

According to Pierre Thomas (Geology Laboratory of Lyon / ENS Lyon) (2011) [1]:

- "It is in these cavities that the temperature is continuously lower or equal to zero, even during the greatest summer heatwaves".
- "Then, a problem is set on the origin of this permanent "cold". It is the subject of a lot of debates since a lot of centuries, and quantitative studies taking account energetical total balance remain to be done. What it can be proposed today? ".
- In the real problem and in the chosen example case, this report indicates that "the Puy de Dôme' Cheire is one of the more beautiful lava-flow of the Puys' chain (*Massif Central*) [...] Surface of this flow is "waving", with bumps and hollows of 5 to 10m high, bumps and hollows resulting from an irregular heap of lava blocks [...]. Altitude is not so more than 780m [...] (*and*) during May 2011, warmest May month since 1900; the external temperature is of 25°C, [...] (*but*) temperature inside the mini-cavity is of 0°C, and will be remained during totality of Summer." [1].

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This description needs to be compared to the one yet done by A. Lepape and G. Colange [2], in the same region in 1941. They report that:

● "The cavities are funnel-shaped very wide-mouthed, with a 5 to 10m deep […] surrounded with trees and bushes and, for a great part, mossy. Ice is formed in the bottom, In a secondary cavity, widely open to the North and with dimensions around 0.5 to 1m. This ice covers the cavity bottom, there is not any on the wall-sides, which are wet…".

● "We have seen these ice-holes during a hot summer day: temperature was very low in the funnel and made up an amazing contrast with the forest one, at only few paces. Inside these very shielded funnels there are not any wind motions and ice have not any tendency to melt. In contrast, ice is formed during all the Summer…".

● "[…] All conditions which will stand motionless the air in contact with soil […] will contribute to reduce still the temperature.".

● 1) There is not air moving inside funnels; 2) temperature is always low inside the bottom funnel-shaped cavity; 3) Air is always wet saturated. […] Near the ground, temperature gradient can be very important […] A darken thermometer, placed on the ground can be sufficiently cooled to be covered by white frost when the ambient air remains around 8 or 10°C above zero […] We think that in the ice-holes all the conditions are brought to form ice: Air always wet saturated; sky looked under a big solid-angle; quiet atmosphere; insulated soil: never sun…".

It can be noticed that the given indications lead to an ambient air relative humidity of about 55-60% which is a "standard or normal' mean value.

The conclusive hypothesis formulated by the authors is then the following:

● "We attribute to the night radiance the necessary cooling to produce ice.".

We have not taken this hypothesis of night radiance [10-11] into account in our work.

On the base of some few geographical and physical indications from P. Thomas, under our disposal, we suggest a new approach to determine the possibilities to remain ice (water solid part) inside the considered volume.

In the real problem, the ice-hole is at the bottom of a funnel-shaped cavity of about 20m in diameter at its surface and with a 10m depth (Figure 9).

Then we will take into consideration a full air funnel-shaped cavity above the truncated volume in which ice will be eventually produced or maintained. This space is submitted to the thermal daily variations, as a function of seasons. These variations can also be dependent on local conditions, the type of soil, its resulting temperature-layers and its action on the upper surface and on the side-walls of the ice-hole volume considered.

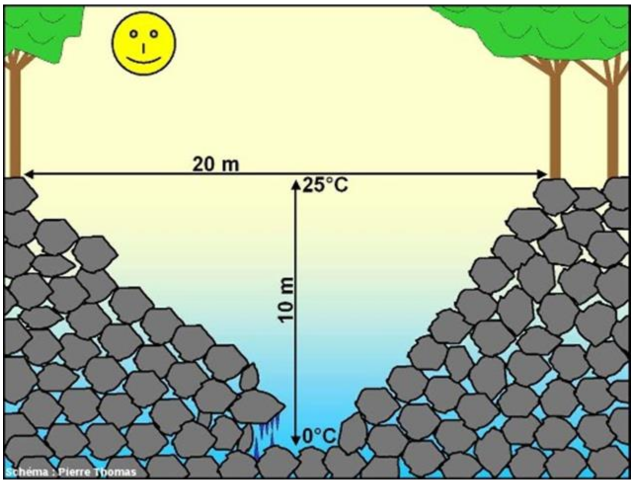

Fig. 9: From P. Thomas (2011) [1]

At the upper ice-hole level, in the bottom of the cavity, this bottom diameter is about 1m. The great funnel-shaped cavity will be named GC.

Our aim is to determine the role of the air, potential insulating material, contained inside this great cavity GC, which will act on the boundary conditions applied to the upper surface of the ice-hole.

The numerical simulation is done for a reduced domain of about 1/10 for GC overlapping the ice-hole as previously defined (**Figure 1**).

For same simplifying reasons than in § 3.1.4 (too great and flat meshes) we have replaced, **in Figure 10**, the truncated GC (in dashed lines) by a cylinder, equivalent in volume (full line)

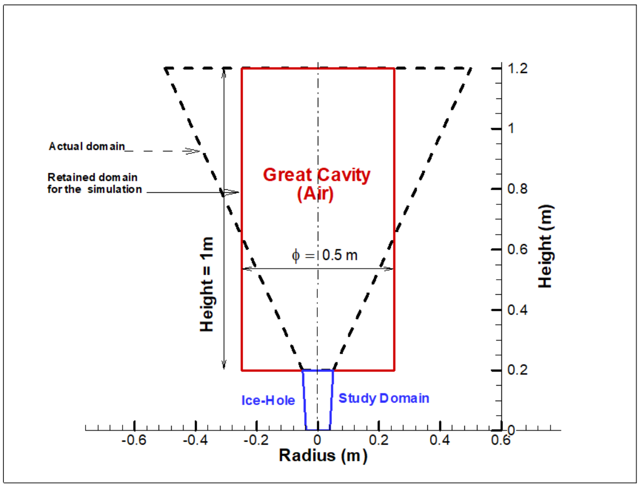

Fig. 10: final domain retained for the numerical simulation: continuous line for the simulation; dashed line for GC.

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This approach is more looking like the swallow-hole "Creux de Glace" which is situated at the South side of Courtelary, in the Swiss Chasseral Chain of mountains.

Situated at an altitude of 1320m, ice remains all the year.". [7]

6.1 Initial boundaries conditions for GC

● The temperature variations at the ground level top of GC are issued of the ambient air temperature mean values for the various "seasons" previously defined. These data are coming from the nearest meteorological station of Pontgibaud (Clermont-Ferrand-Aulnat, Puy de Dôme, France) [8]. (see **§ 2.4**.).

● From these mean seasonal temperature values of the ambient air, on the upper part of GC, the soil temperature will be stratified so that it reaches the new hypothetical values for a frozen soil (- 2°C) or unfrozen one (0°C) at the ice-hole bottom.

a) - 2°C at 1.5m in depth from the ground level, which permits to obtain the "frozen soil" conditions around the studied domain (ice-hole);

b) 0°C at 1.5m in depth from the ground level, to obtain the "unfrozen soil" conditions.

● For the air temperature variations inside GC, calculations start at the initial time t = 0 (6h am) in conditions considered as stabilised, near the stationary state of the external ambient air at the ground level surface of GC. Then the dynamical and thermal states of the air, at the calculations start, are obtained by the corresponding stationary problems.

● Thermal calculations for the side-walls and bottom of GC are made by taking the natural convection and the air-side-walls thermal exchanges in GC - but also for the ice-hole - into account.

Then the bottom GC temperature is the one applied to the upper open-air surface of the ice-hole.

On the ice-hole side-walls there are small thermal exchanges, at each level, between the soil and the side-walls.

● Thermal characteristics of soil material are taken in considerations (following **Table 1** [12]).

Unlike their thermal conductivity evolution in relation with water content, as it can be found in [13], is not considered.

● Due to the lake of specific indications on the local material surrounding the ice-hole we have chosen the granite and this walls material will be considered as homogeneous.

Because we have taken the natural air convection inside GC into account, the calculation time steps need to be lower (1s instead of 5s). Calculation times are accordingly longer.

As previously, for identical reasons, the results obtained for the two conditions of frozen and unfrozen soils and for Winter and Summer, these more representative seasons, will only be presented.

Rocks type	Thermal conductivity *k* (W/mK)			Volumetric thermal capacity ρC (MJ/m³K)
	Min.	Typical Value	Max.	
Basalt	1.3	1.7	2.3	2.3 – 2.6
Gabbro	1.7	1.9	2.5	2.6
Granit	2.1	3.4	4.1	2.1 – 3.0
Clayey Schists	1.5	2.1	2.1	2.2 – 2.5
limestone	2.5	2.8	4.0	2.1 – 2.4
Sandstone	1.3	2.3	5.1	1.6 – 2.8
Moraine	1.0	2.0	2.5	1.5 – 2.5
Clay/dry silt	0.4	0.5	1.0	1.5 – 1.6
Clayey or silty rocks	1.1	2.2	3.5	2.1 – 2.4
Water (+10°C)	0.58			4.19
Ice(-10°C)	2.32			1.87
Air (0-20°C, sec)	0.02			0.0012

Table 1: Thermal characteristics of the soil materials (from [12 & 13])

6.2. Frozen soil: (- 2°C at 1.50m in depth)

First, the following two Figures illustrate the temporal and spatial stratification evolution of the temperature inside a granite soil submitted to a daily sinusoidal variation of the external ambient air temperature.

Results obtained with various soil materials, clayey-schist (shale) or granite, indicate that the temperature, which will determine the one of the GC bottom-level, and of all the surrounding side walls of the ice-hole, situated below 1m in depth, is reached, in fact, at about 0.60m. Then, soil temperature remaining constant below 0.6 m will be the one applied on the GC side walls in touch with the soil layers matching with. The following Figure10 show the fast temperature fall inside this material which lead to an about - 2°C temperature at the soil layer in contact with the GC bottom level. Consequently, all the side walls of the ice-hole, except its upper surface, in touch with the air temperature inside GC at its bottom level, will be submitted to this soil temperature.

6.2.1 Winter: external air amplitude (- 5°C to + 10°C)

● **Figure 11** shows the temporal and spatial evolution (stratification) of the applied external air temperature inside a granite soil during a daily (24h) sinusoidal ambient temperature variation.

A stabilized negative temperature (- 2°C) corresponding to the frozen soil condition at a deep of 1.50m is reached at a depth between 50-60cm.

These results must be compared to the ones published in a study on the Canadian wells [12] showing that, on a plane ground level, to be out of freezing, 1m in depth is recommended:

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- "larger is the depth, more the temperature variations of the soil decrease (action of the external temperature is reduced […] fluctuations being without effect beyond some meters.).".

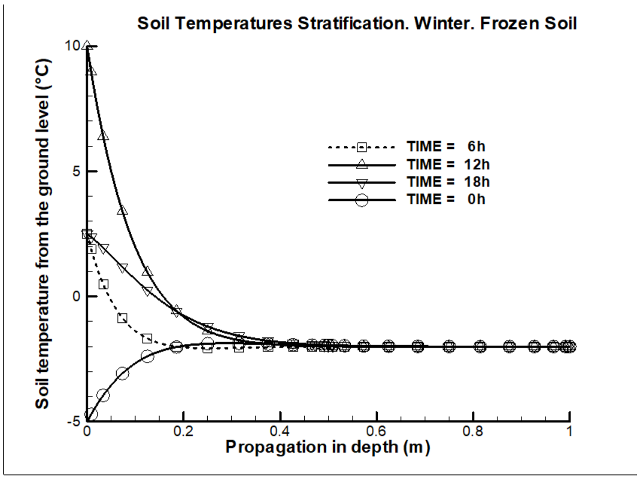

Fig. 11: evolution (stratification) in depth of the applied external air temperature inside a granite soil during a Winter sinusoidal daily (24h) variation.

● **Figure 12** is representative of a soil slice and shows the spatial stratification of the soil layers at various moments of the daily temperature variations. These figures clearly point out that temperature remains constant at – 2°C (level N°4), below 0.6m in depth, whatever the external air temperature. In these conditions the solid part of water, the initial ice volume, cannot be modified inside the ice-hole situated underside the GC bottom level

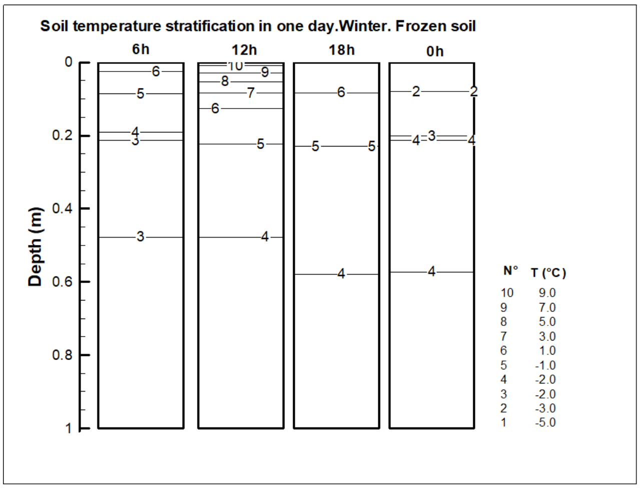

Fig. 12: spatial stratification, soil layers temperatures in a soil slice, at various moments of a Winter daily temperature variations.

● **Figures 13a and 13b** represent the variations of the external air temperature in GC, situated above the ice-hole. They show isotherms and air movements inside GC at noon (12h am), during the maximal value of temperature (+ 10°C). These movements are resulting from the natural convection, without any forced air circulation.

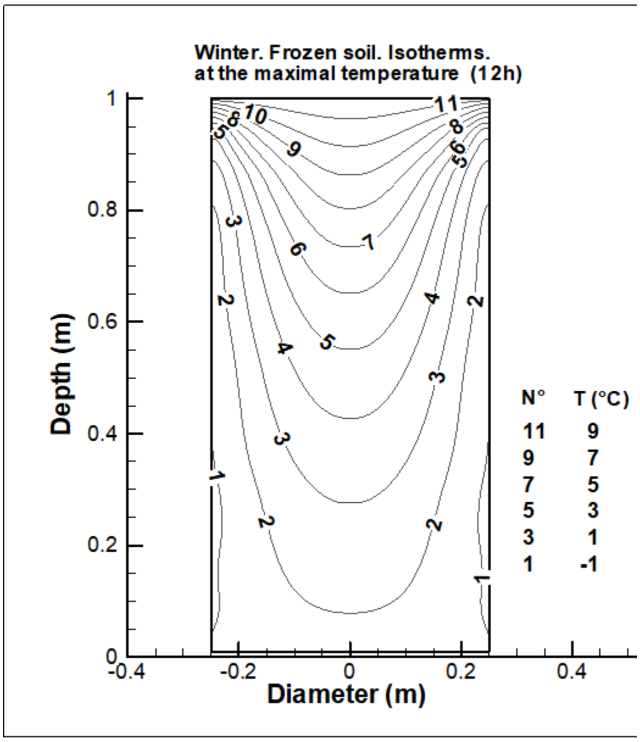

Fig. 13a: stratification of the external air temperature inside GC

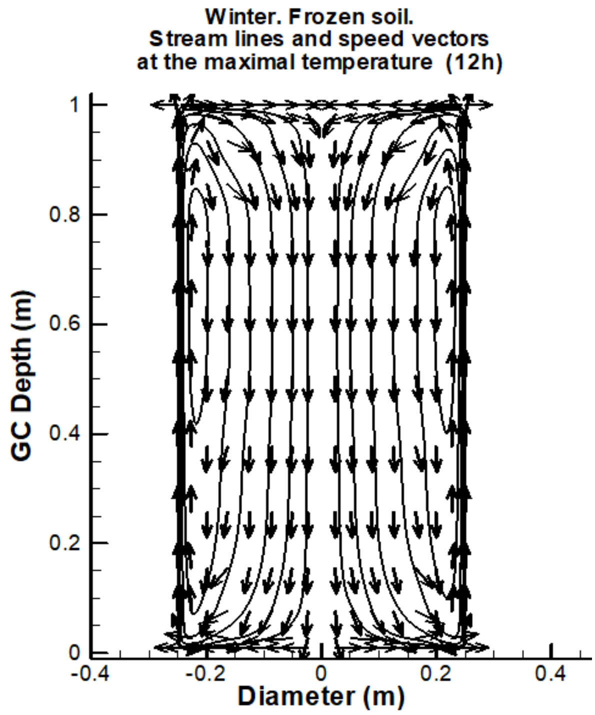

Fig. 13b: air movements inside GC

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It can be pointed out that, when external temperature reaches its top value, the bottom level of GC, at 1m in depth, upper surface of the ice-hole, is completely below the fusion point (0°C).

Consequently, totality of the ice-hole will be surrounded by temperatures below 0°C and ice volume can be totally maintained.

● **Figure 14** compares the evolution of the external ambient temperature at the ground level, upper surface of GC, with the one at its bottom level, upper surface level of the ice-hole.

At the same time, side walls of the ice-hole are in contact with the soil, of which temperature remains at about – 2°C (**see Figures 11 & 12**).

At the bottom level of GC, the maximal temperature values fell more than 10°C, and the amplitude variations were reduced from 15°C (- 5°C to + 10°C) to about 2°C (- 0.5°C to -2.5°C) (see **also Figure 13a**).

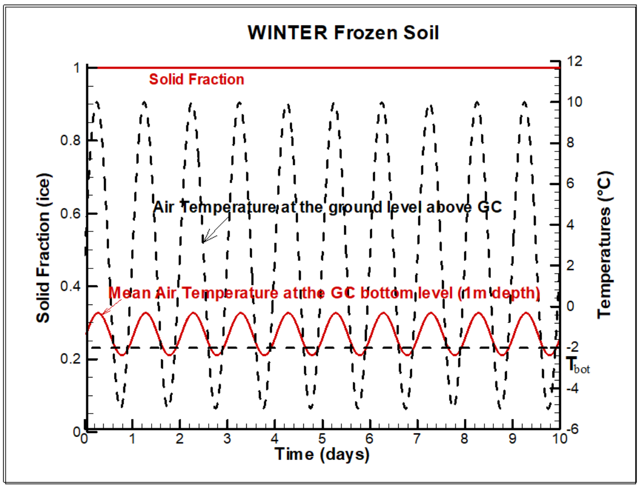

Fig. 14: daily variations of the ice percentage (solid fraction; red continuous upper line) and of the mean temperature inside the ice-hole (lower red continuous line), compared to the external air temperature (dashed line)

● On the other hand, the minimal temperature value at the bottom level of GC is practically equal to, slightly lower than – 2°C (T_{bot} fixed at – 2°C). It means that the air temperature at the GC bottom level remains next the one of the in-contact soil layers, very slightly modified by the air temperature of the bottom GC level.

Then it appears that, all along this Winter season, for the external air mean temperatures considered, the solid part of water (ice) remains at its maximal value (100%).

● These two phenomena confirm the fact that the temperature layers of the soil act, supervise and bound the temperature of the ice-hole side walls, except for its upper surface.

This later is submitted to the isotherm taking place at the GC bottom level (Figure 13a).

● 24h period is the same for the signals but there is a transit delay of about 45mn between the higher and the lower GC surfaces. This can be assigned to the thermal characteristics of the soil material surrounding GC and the thermal characteristics of the ambient air inside.

6.2.2. Summer: external air amplitude (+ 5°C to + 20°C)

As for Winter, the following Figures illustrate the temporal and spatial temperature evolution during a sinusoidal daily (24h) temperature variation, in stabilised conditions, into the soil as a function of the depth (**Figure 13a and 13b**) and by stratification in the layers of a soil slice (**Figure 16).**

● **Figure 15** shows a very fast temperature fall inside this homogeneous granite soil (by hypothesis) which can lead to a negative temperature (about - 2°C) at the GC bottom level.

As for Winter, this temperature is reached at about 60 cm in depth.

Consequently, this temperature will be the one applied to the ice-hole side walls, except for its upper surface in contact with the air temperature at the GC bottom-level.

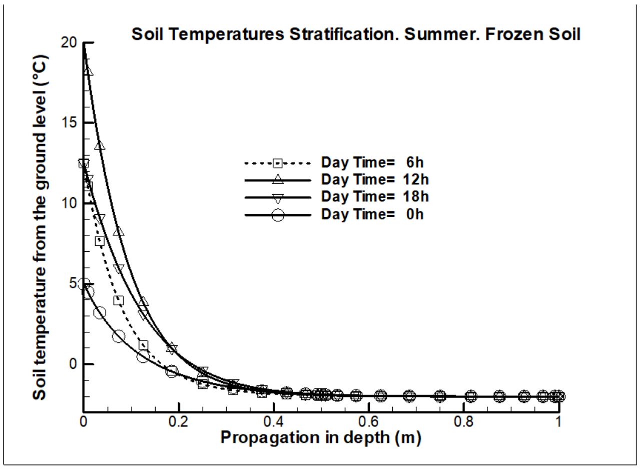

Fig. 15: evolution (stratification) in depth of the applied external air temperature inside a granite soil during a Summer sinusoidal daily (24h) temperature variation.

● **Figure 16** illustrates the spatial and temporal daily evolution (during 24h) of the external air temperature stratification inside a slice of the soil, surrounding GC and above the ice-hole. Only the ice-hole open air upper surface, at the GC bottom level, can be submitted to the transmitted atmospheric air temperature.

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It can be noted that all the side walls of the ice-hole, are surrounded by a negative temperature (- 2°C) below the melting point. Level N° 3 (0°C) of Figure 16 indicates the zone under which it is possible to obtain the solidification effect (ice).

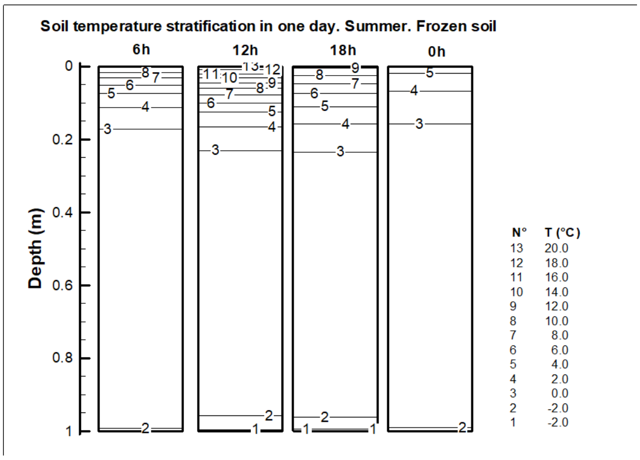

Fig. 16: spatial stratification, soil layers temperatures in a soil slice, at various moments of a Summer daily temperature variations

- **Figures 17a and 17b** show the isotherms and air movements inside GC for the day maximal temperature, + 20°C, at noon (12h am).

It appears that, even in Summer, the bottom mean temperature of GC could be evaluated around + 3°C, varying from + 0.5 to + 5.5 °C.

As a result, the GC presence above the ice-hole has an apparent strong absorption and smoothing effect, as far as the GC bottom level, on the variations of the external air temperatures. The maximal temperature value is reduced from + 20°C to + 5.5°C, and the minimal value is lower than + 1°C, near to the melting point.

The resulting mean temperature at the GC bottom level is around + 3°C, very low for this season.

This can lead to a great possibility of solid part of water (ice) in the ice-hole, due to that side walls and bottom of the ice-hole, below 1 m deep, are surrounded by the frozen soil

- **Figure 18** compares the daily variation of the external ambient air, with the air temperature inside GC and the ice percentage inside the ice-hole. The absorption role of GC is clearly shown. Submitted to a daily stabilized and regular sinusoidal amplitude variation of temperature, the solid part of water (ice) is regularly decreasing and leads to a stabilised 55% minimal value, in about 25-30 days, with regular and periodical very brief maxima at about 75%.

Then it seems possible that, in the defined hypothetic soil conditions, even in Summer, around 50% of solid part of water (ice) could remain inside the ice-hole.

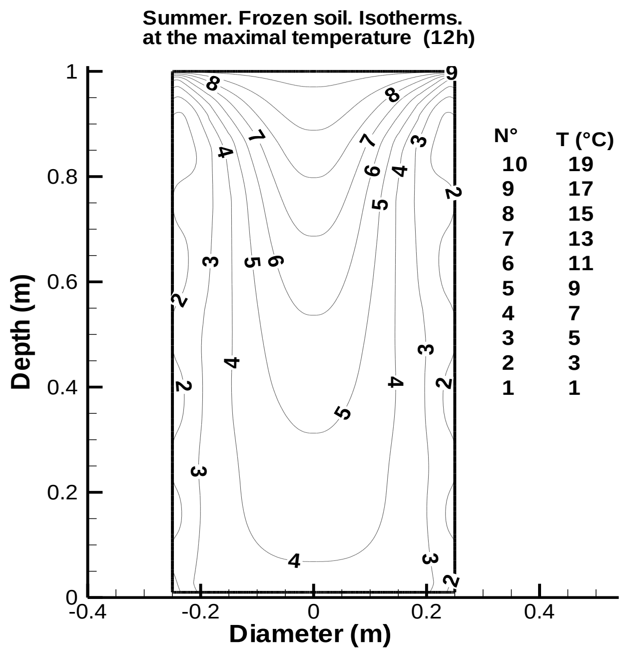

Fig. 17a: stratification of the external air temperature inside GC

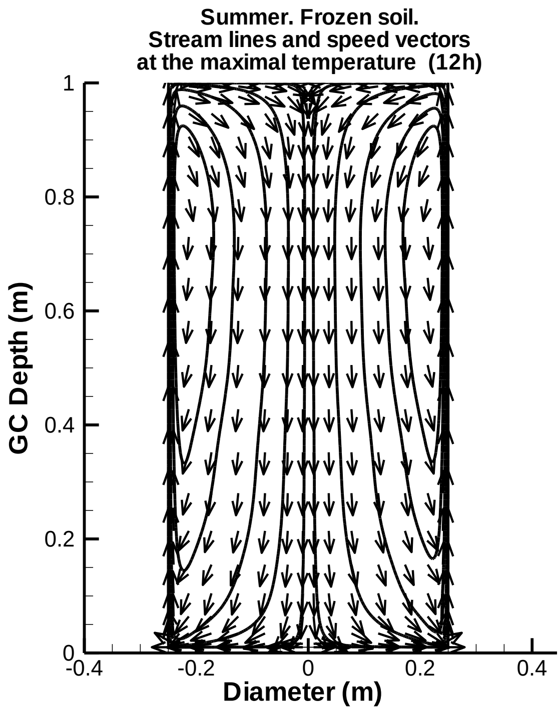

Fig. 17b: air movements inside GC

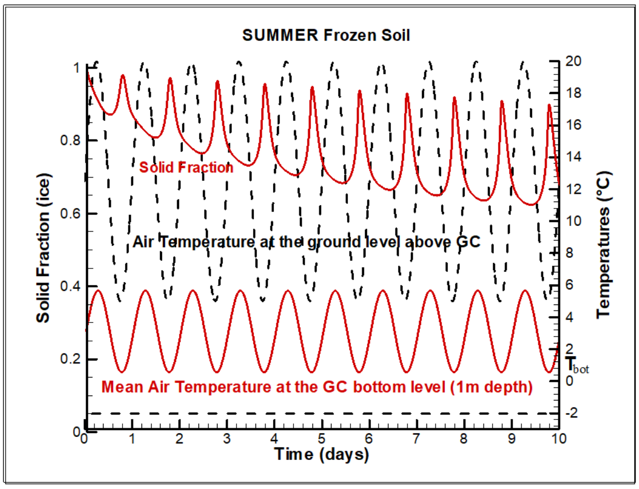

Fig. 18: daily variations of the ice percentage (solid fraction; upper continuous red line) and of the temperature at the GC bottom (lower red continuous line), compared to the external air temperature (black dashed line)

6.3. Unfrozen soil: (0°C at 1.50m in depth)

6.3.1 Winter: external air amplitude (- 5°C to + 10°C)

As for the frozen soil hypothesis, the choice of an unfrozen soil (0°C at 1.50m in depth), whatever the season, must modify the remaining ice percentage inside the ice-hole.
This is illustrated by the following **Figure 19** which can be compared with **Figure 15**

- **Figure 19** shows a very fast fall of temperature inside this granite soil (by hypothesis) which can lead to a temperature near the melting point (0°C) at the GC bottom level. As for the frozen soil case, this temperature is reached in lower than 1m in depth at about 50-60cm.

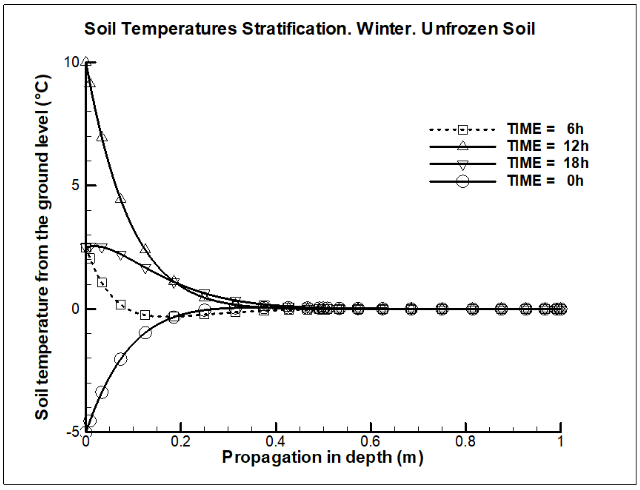

Fig. 19: evolution (stratification) in depth of the applied external air temperature inside a granite soil during a Winter sinusoidal daily (24h) temperature variation.

Consequently, this temperature will be the one applied to the ice-hole side walls, except for its upper surface in contact with the ambient air temperature transmitted inside GC down to its bottom level.

- **Figure 20** illustrates the spatial and temporal daily evolution (during 24h) of the external air temperature inside the unfrozen soil surrounding GC, and above the ice-hole.

It appears clearly than below the level N° 4 (0°C) the solid fraction of water (ice), in the ice-hole, below the GC bottom, can lay an important role as a function of time.

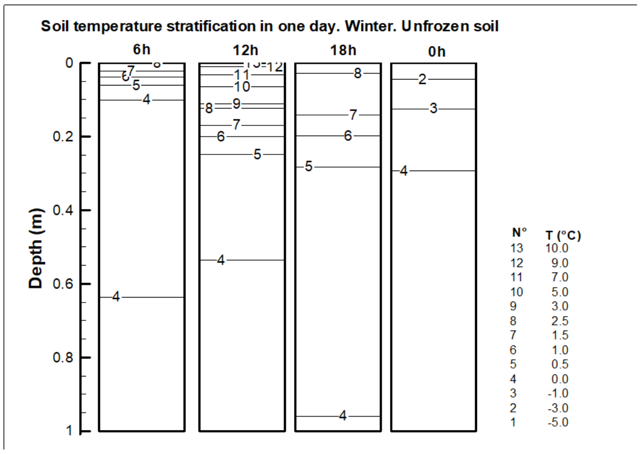

Fig. 20: spatial stratification, soil layers temperatures in a soil slice, at various moments of a Winter daily temperature variations.

- **Figures 21a and 21b** show the isotherms and air movements inside GC for the day maximal temperature (+ 10°C) at noon (12h).

As previously seen, the GC presence above the ice-hole has a strong temperature absorption effect on the variations of the external air temperatures, up to the GC bottom level. The maximal temperature value is reduced from + 10°C to + 1.3°C, and the minimal one is lower than + 0.5°C.

The resulting mean temperature at the GC bottom level, upper surface of the ice-hole, is close to the melting point.

This can lead to a great possibility of ice presence in the ice-hole due to that, below 1m in depth, the side walls and the bottom of the ice-hole are surrounded by the unfrozen soil at 0°C.

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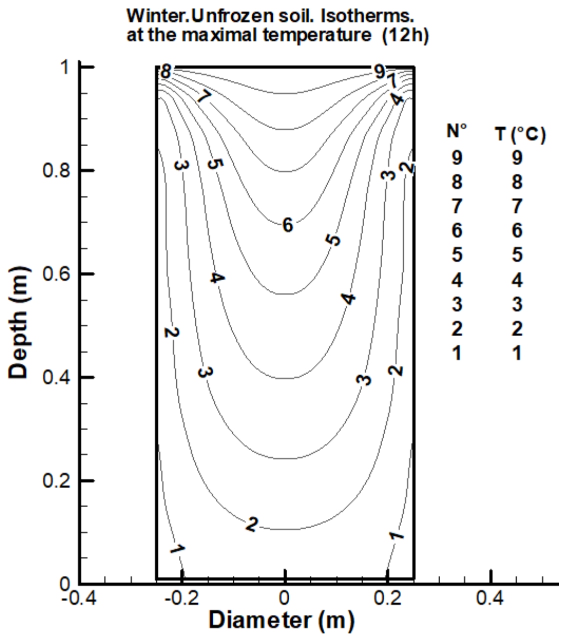

Fig. 21a: stratification of the external air temperature inside GC

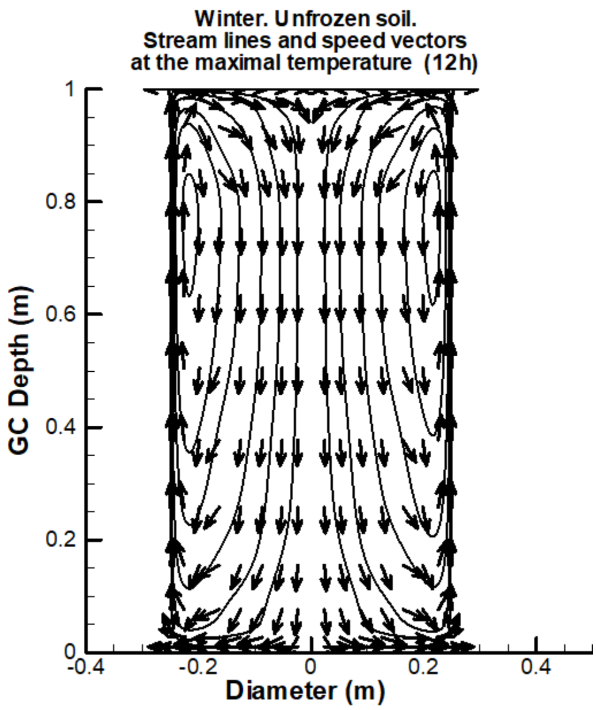

Fig. 21b: air movements inside GC

● **Figure 22**, by comparing, the daily variation of the external ambient air, with the air temperature inside GC and the ice percentage inside the ice-hole, points out and confirm the absorption role of GC.

At the GC bottom level, the air temperature is around the fusion point (0°C) varying between + 1.3°C and –0.7°C in relation with the surrounding soil layer at 0°C (T_{bot}).

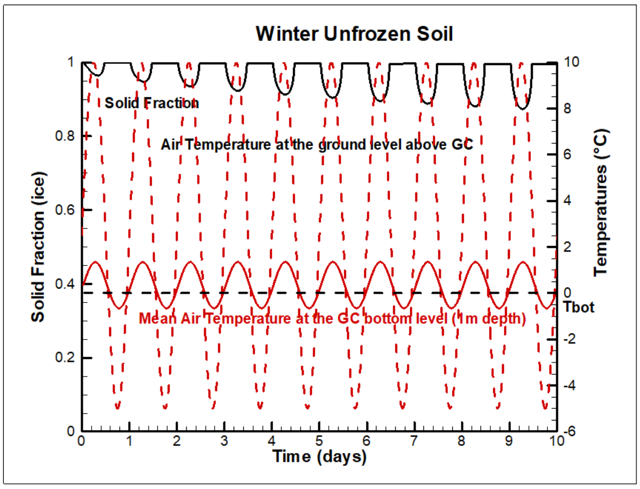

Figure 22: daily variations of the ice percentage and of the temperature at the GC bottom (continuous lines), compared to the external air temperature (dashed line). T_{bot} = Temperature of the soil layer at 1m deep.

● Submitted to a daily stabilized and regular sinusoidal amplitude variation of temperature, the solid part of water is regularly decreasing and leads to a stabilised minimal value around 85%., in about 25-30 days. This minimal solid part (ice) value, delayed by comparison with the maximal external air temperature value (+ 10°C), takes place at around + 7.5°C.

Below an external temperature value of + 3°C the ice percentage remains at 100%.

6.3.2. Summer: external air amplitude (+ 5°C to + 20°C)

● **Figure 23** shows a very fast fall of temperature inside this granite soil (by hypothesis) which can lead to a temperature near the fusion point (0°C) at the GC bottom level.

As for the frozen soil case, during Winter, this temperature is reached at about 60cm in depth.

Consequently, this temperature will be the one applied to the ice-hole side walls, except for its upper surface in contact with the GC bottom surface.

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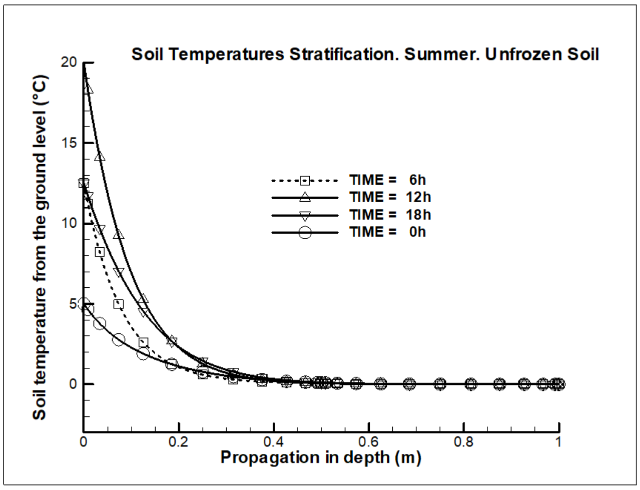

Figure 23: evolution (stratification) in depth of the applied external air temperature inside a granite soil during a Summer sinusoidal daily (24h) temperature variation.

- **Figure 24** illustrates the spatial and temporal daily evolution (during 24h) of the external air temperature inside the unfrozen soil surrounding GC, and above the ice-hole.

It appears clearly that, in these conditions, during the summer period, below the GC bottom level, where the temperature is around 0°C (level N° 1), it will be very difficult to obtain an important solid part of water (ice) with an unfrozen soil equally at 0°C.

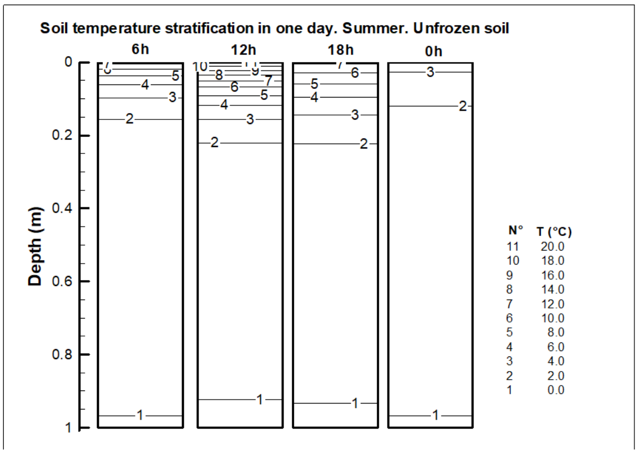

Figure 24: spatial stratification, soil layers temperatures in a soil slice, at various moments of a Winter daily temperature variations.

- **Figures 25a and 25b** show the isotherms and air movements inside GC for the daily maximal temperature (+ 20°C) at noon (12h).

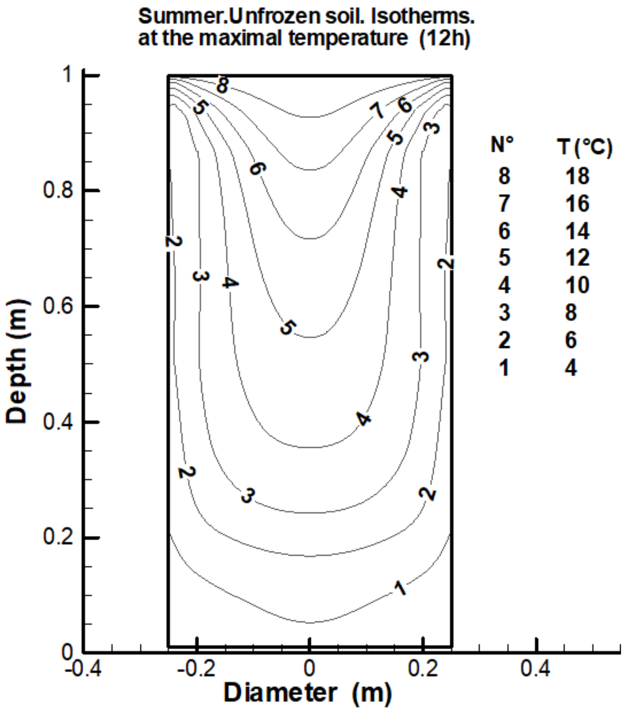

Fig. 25a: stratification of the external air temperature inside GC

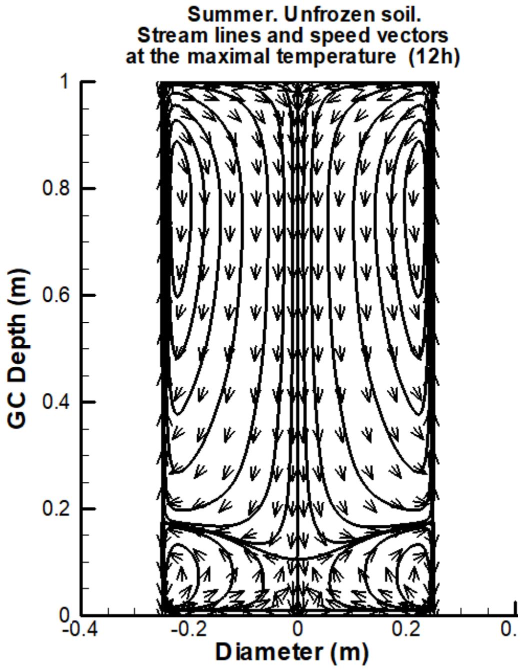

Fig. 25b: air movements inside GC

The GC presence above the ice-hole plays the role of an absorber of the external air temperature variations, up to the GC bottom level, The maximal temperature value is


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reduced from + 20°C to about + 3.5°C, and the minimal one is lower than + 2.5°C.

The resulting mean temperature at the GC bottom level, upper surface of the ice-hole, is very low for a Summer "season".

This can lead to a reduced possibility of solid part of water (ice) in the ice-hole, due to that side walls and bottom of the ice-hole, below 1m deep, are surrounded by the unfrozen soil at 0°C.

- **Figure 26**, by comparing, the daily variation of the external ambient air, with the air temperature inside GC and the remaining ice percentage inside the ice-hole, points out, one more time, the ambient air temperature absorption and smoothing role of GC.

At the GC bottom level, top level of the ice-hole, the air temperature is around + 3°C, varying between + 3.5°C and + 2.5°C not so far of the surrounding soil layer at 0°C (T_{bot}).

Submitted to a daily stabilized and regular sinusoidal amplitude variation of temperature, the solid part of water (ice) is regularly decreasing and leads to a minimal value around 45%., in about 12 days. But, continuously submitted to this regular temperature variations, it tends to zero (total fusion of the ice) in about twenty periodical variations of 24h.

It can be noted a similar behaviour in Spring, with an external temperature varying from + 16°C to – 2°C.

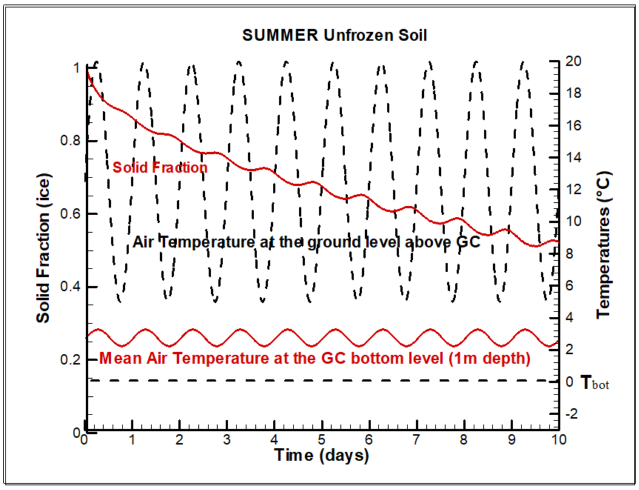

Figure 26: daily variations of the ice percentage (solid fraction; upper red continuous line) and of the mean temperature at the GC bottom (lower red continuous line), compared to the external air temperature (sinusoidal black dashed line).

During this season there is a slow regular decrease of the solid part of water (ice) leading to an alternation of the ice percentage inside the ice-hole moving from 100% to 30% in sixty daily periods which is equivalent to 2 months.

Then it appears that, up to the end of Spring, on the base of the chosen hypothesis, there is a possibility to observe ice in an ice-hole.

It can be noticed also that, in the natural state, so regular temperatures variation in a so long time do not take place.

7. Comparisons between the temperature evolutions inside GC, as a function of the frozen or unfrozen soil, for two seasons, and the resulting ice percentage in an ice-hole.

7.1. Frozen soil

As previously indicated only the results obtained for Winter and Summer seasons will be presented and compared.

- Reminder: soil temperature is hypothetically considered at - 2°C at 1.50m in depth (T_{bot}). The GC bottom level (1m in depth) and side walls of the ice-hole are also at this temperature value.

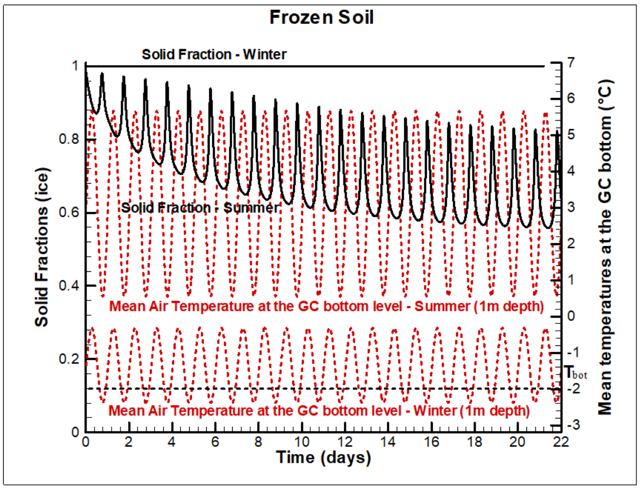

Figure 27: comparison between the ice percentage (solid part; black continuous lines) and the external air temperature (upper red dashed line) and mean temperature at the GC bottom level (lower red dashed lines) during Winter and Summer.

As indicated in the **Figure 27**:

- During the Winter season (T_{ext} from – 5°C to + 10°C) the GC bottom mean temperature is always negative (- 1.5°C), near the one of the soil-layer (- 2°C) (see **Figure 11**), and, consequently, ice cannot melt (see **Figure 14**).

- During the Summer season (T_{ext} from + 5°C to + 20°C), the GC bottom mean temperature is always positive, varying between + 0.5°C and about + 5.5°C, due to the natural convective effect inside GC (**Figures 17a & 17b**).

Consequently, the percentage of ice is regularly decreasing with the passing days (see **Figure 18**).

In about 30 days, this minimal tends to 50% varying up to 75% for the GC lower temperature.

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Then, these results seem to indicate that, in conditions which are similar the ones hypothetically selected, ice could not be totally melted.

7.2. Unfrozen soil

● Reminder: soil temperature is hypothetically considered at 0°C° at 1.50m in depth (T_{bot}). The GC bottom level and side walls of the ice-hole are also at this temperature value.

As we can see in **Figure 28**:

● During the Winter season (*Text* from – 5°C to + 10°C) the GC bottom mean temperature is varying between – 0.7°C and + 1.3°C (see Figures 21a & 21b), near the one of the soil-layer (0°C) (see Figure 22). Ice melts very slowly with a minimal percentage around 75% in about 30 days.

● During the Summer season (*Text* from + 5°C to + 20°C), the GC bottom mean temperature is always positive, varying between + 2.2°C and + 3.3°C, due to the natural convective effect inside GC (see Figures 25a & 25b).

Ice melting, which takes normally place on the upper surface of the ice-hole, is enhanced by the melt all along the side walls maintained at 0°C.

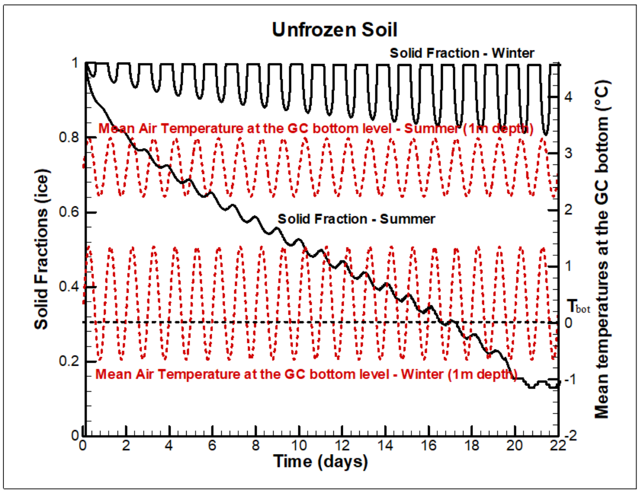

Figure 28: comparison between the ice percentage (solid part; black continuous lines) during Winter (upper black) and Summer (lower black) and the external air temperature and mean temperature at the GC bottom level (red dashed lines) : Winter (lower red) and Summer (upper red).

Consequently, a very rapid ice melting occurs, about 50% in 10 days (**Figure 26),** and ice could be completely melted in about 20 days (**Figure 28**).

It must be noted that, as forecasted, the GC bottom level temperature is increasing from Winter to Summer and this temperature becomes positive since Spring. During Spring it could be possible to find approximately 30% ice in an ice-hole submitted to the hypothetical conditions considered.

Nevertheless, during Summer, this mean temperature value does not seem to reach more than + 3°C with small amplitude variations less than ± 1.5°C.

7.3. Dephasing behaviour: comparisons between frozen and unfrozen soils

Dephasings as a function of the seasonal temperatures are measured during the permanent regime stabilized generally over the 20th day. Calculations are numerically done by comparing the maximal external air values (T_{ext}), at the ground level, with the ice-hole mean temperature ones (T_{mean}) and the minimal solid part in the considered volume.

These dephasings represent the needed time necessary to move from solid to liquid phase in relation with the external applied temperature, as illustrated in **Figure 29.**

● In a frozen soil, during Winter, with the ice-hole side walls at - 2°C, ice remains at its maximal percentage (100% of its initial volume). In these conditions we cannot take a dephasing with the external temperature into account. Only the dephasing between the summer minimal external temperature and the ice-hole mean temperature can be evaluated, and therefore the resulting ice percentage.

● In a frozen soil, during Summer, this ice volume could be reduced to 50% after about 25 days before it stabilises (**Figure 27**).

The following **Figure 29** illustrates the in-time solid part variation – between 50 and about 80% - as a function of the daily temperature. Dephasing between the ice minimum part and the maximum of the external temperature is around 3h 45mn during Summer.

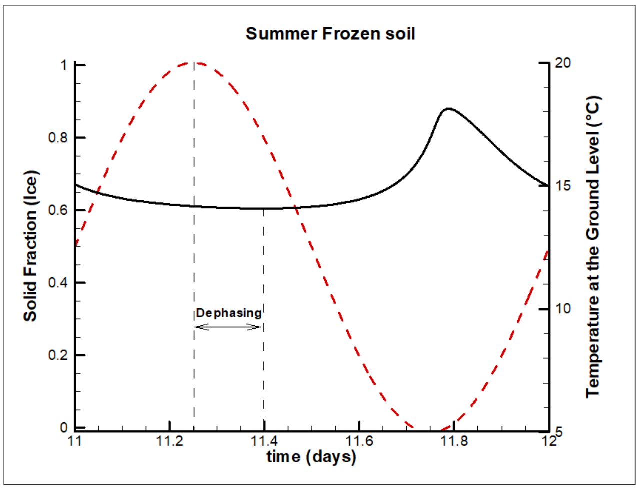

Figure 29: comparison between a daily external temperature variation (dashed line) and the ice percentage evolution (continuous line) in the same time

From **Figure 30**, it can be noted that this dephasing is very dependent on soil conditions whose temperature determines the one inside the ice-hole (T_{mean}) until Spring.

By comparing with **Figure 8** dealing with dephasings in the case of an ice-hole without GC above it, Spring appears as

the crucial season from which dephasing is more and more increasing.

In the two cases (ice-hole without or with GC above), the dephasings are about 2 hours higher for an unfrozen soil than for a frozen one.

On the base of the local meteorological data, the temperature variations are not obviously so regular than the ones imposed in the present simulation. So, ice remaining will depend essentially on the ratio between the higher and the lower temperatures all along the seasons and the months. Meteorological temperature daily irregular variations are also submitted to the strong temperature smoothing effect in relation with the cavity depth.

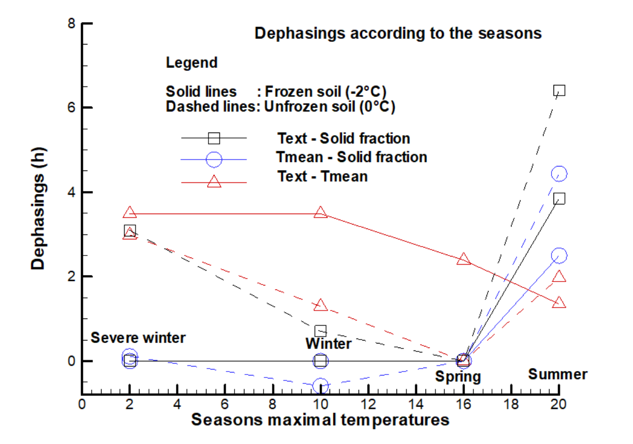

Figure 30: Dephasing evolution as function of the maximal temperature of the seasons

8. Conclusion and prospects

In order to explain the existence of ice-holes and their presence even during unfavourable meteorological conditions of temperature (Spring or Summer seasons), a prime simplified numerical approach is suggested. It is based on some laboratory experiments associated with numerical modelling, done in reduced volumes to study some phase changing (gas, liquid, solid) materials.

In this event we are dealing with water in its liquid and solid (ice) phases.

The present study of the ice melting in a small volume submitted to a continuous heating of its top level, while the bottom surface was maintained at a constant temperature of – 5°C, has been made suitable to this situation.

With the results obtained, it appears that the ice volume cannot be totally melted, whatever the temperature (up to 30°C), even if it is decreasing, before to be stabilized, in 9-10 days.

Then, continuous heating was replaced by a sinusoidal daily variation (24h) of the temperature with amplitude variations as a function of the mean seasonal temperature values issued from local meteorological data.

First, we have considered a small ice-hole volume with its top at the ground level. Two conditions for the maintenance of the bottom level temperature were considered: a “frozen soil” with a bottom level maintained at – 5°C and side walls at – 2°C, and an “unfrozen soil” with a bottom level maintained at + 2°C and side walls at + 5°C.

In these conditions, temporal evolution of the water solid fraction (ice) of a defined volume was studied during some daily periods of 24h up to the stabilization phase of the process. All the seasons were studied but only Winter (favourable temperatures of the external air) and Summer (unfavourable temperatures) are presented.

- In the frozen soil conditions, during Winter (T_{ext}: - 5°C to + 10°C), as a function of the daily temperature, ice remains between 83 and 100% of its initial volume. During Summer (T_{ext}: + 5°C to + 20°C) the initial ice volume is firstly decreasing down to a stabilized value around 50%, generally reached in about 8-9 daily periods.

This is due to that the ice-hole bottom level is always kept at a – 5°C temperature.

- In the unfrozen soil conditions, during Winter, very important oscillations (from 5 to 100%) in the percentage of the ice volume appear, before to be stabilized in about 8-9 daily periods.

During Summer, the ice volume decreases regularly to a very small value around 3% in about 5-6 24h sinusoidal period (“days”).

In the two soil conditions it can be pointed out some phase delays between the minimal external temperature and the minimal mean temperature of the ice-hole linked with the maximal percentage of ice in this later.

Secondly, we have considered the natural ambient air conditions in which ice-holes can be observed.

They generally require the presence of a great cavity, a big hollow, of some meters in depth.

Consequently, we have attempted to define the possible role played by this cavity set above. This one will determine the true external temperature applied to the top surface of the ice-hole situated at the bottom of the cavity. All the other side walls of the ice-hole will be submitted to the soil temperature surrounding them.

Then it was necessary to assume some hypothesis on the soil nature and the temperatures which can be reached at depth lower than the one of the ice-hole open-air top and its surrounding walls.

As previously, two temperature conditions were chosen: frozen soil (- 2°C at 1.50m in depth) and unfrozen soil (0°C at 1.50m in depth). The mean seasonal temperatures are remaining the same.

In summary, from the numerical results obtained with these new hypothesises, we can say:

- Only the ice situated at the ice-hole top surface, in contact with the external air, can melt.
- Concerning the side walls of the ice-hole in contact with the surrounding soil, being considered as watertight: there is not water in the lower part of the ice-hole volume.
- Ice presence is completely dependent on the temperatures all around the side-walls.
- The presence of a cavity above the ice-hole and its depth, the nature of the soil surrounding this cavity and the ice-hole, and the environmental conditions favourable to an unforced air circulation will act on the external air temperature transfer to the top surface of the ice-hole.

It appears clearly that this cavity plays an important role as a very efficient heat absorber.

- Finally, in such similar topological conditions, seasonal temperature conditions characterized by the ratio between the highest and the lowest mean temperature values, their amplitude and period duration, will determine the presence or not of ice inside the ice-hole.

A modelling of the meteorological data issuing from the nearest meteorological station of Pontgibaud (Massif Central, France) would permit to check our hypothesis and to get closer to the real situation considered in this study.

Works on this research subject are running and lead to interesting results.

Contribution of the authors

The two authors were members of the same University of PAU (FRANCE) in two different laboratories, but, since the year 2000, they have established a collaboration by working jointly on various subject of research.

The main author, J. Batina, is emeritus lecturer in applied mathematics and R. Peyrous research doctor engineer in gas discharges. They have published some common papers in international reviews (before 2003 and 2013 and 2018) and, since this year, participated in 4 various congresses under the care of the French Thermal Society (SFT).

References

[1] Pierre Thomas, Les trous à glace de la Cheire du Puy de Côme (Puy de Dôme), Laboratoire de Géologie de Lyon / ENS Lyon, (27/06/2011), https//planet-terre.ens-lyon.fr

[2] Adolphe Lepape et Georges Colange, *Sur la formation de la glace, en été, dans les coulées volcaniques d'Auvergne*, Comptes-Rendus de l'Académie des Sciences, Physique du Globe, 25 Août 1941, pp 292-294.

[3] Yves Nédonsel, Le massif de la Sainte Baume et la production de glace naturelle : les glacières de Fontfrège, Le Monde alpin et rhodanien. Revue régionale d'ethnologie, n°2-3, pp. 103-125 (1981).

[4] Moll L., Encyclopédie pratique de l'agriculture, Paris (1863).

[5] Batina J., Blancher S., Kousksou T., Modelling of a PCM cell melting submitted to an unsteady heat flux. 2eme Congrès de l'Association Marocaine de Thermique (AMT'2012), April 2012, Casablanca (Morocco). CDROM, 6 p.

[6] Batina J., Blancher S., Kousksou T., Modelling of melting process sin a cell containing a phase change material, Congress of MFTP, Agadir (Morocco), April 2012.

[7] Wikipedia: https://fr.wikipedia.org/wiki/Creux-de-Glace.

[8] Wikipedia: https://www.infoclimat.fr/stations-meteo/analyses-mensuelles.php

[9] Batina J., Blancher S., Kousksou T., "Modelling of a Phase Change Material melting process heated from below using spectral collocation methods", *International Journal of Numerical Methods for Heat & Fluid Flow*, Vol. 24 No. 3, pp. 697-734, April 2014, http://dx.doi.org/10.1108/HFF-03-2012-0062

[10] Barde Olivier, les radiations infra-rouges diurnes et nocturnes, Physique du bâtiment, Ingénieurs et architectes suisses, N° 24, 13 novembre 1991, http://www.e-periodica.ch.

[11] J. Jamin, Sur le rayonnement nocturne. J. Phys. Theor. Appl., 4 (1), pp.245-247, 1885-. 1051/jphystap: 018850040024500. jpa-00238339

[12] https://energieplus-lesite.be › Données › Caractéristiques thermiques des sols - Energie Plus Le Site

[13] https://www.guidebatimentdurable.brussels › déterminer les caractéristiques du sol