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DENDRITIC ICE GROWTH IN SUPERCOOLED WATER INSIDE CYLINDRICAL CAPSULE

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ABSTRACT

The supercooling water was studied experimentally inside cylindrical capsules used for cold storage process. The transfer fluid (TF) is a water-alcohol mixture (50% vol.), controlled by a constant temperature bath (CTB). Temperatures varying with time are measured inside and outside the capsule. Cylinder with internal diameter and thickness of 45 mm and 1.5 mm, respectively, were made in acrylic material. The water supercooling period and the nucleation temperature were investigated for different transfer fluid temperatures. The results indicate that the dendritic ice growth, for different thermocouples position, is as a function of the transfer fluid temperature. The process of nucleation varies with the transfer fluid temperature. The temperature of the phase-change material (PCM) varies during the nucleation time, and, in same cases, the dendrites disappear (formed during the nucleation time) and the solidification process continues with a smooth interface.

1. INTRODUCTION

Water is widely used in thermal storage system as phase-change material (PCM) due to its advantages: high value in latent heat, stable chemical properties, low cost and easy acquisition, no environmental pollution concern, and compatibility with the materials used in air-conditioning equipment. However, there are a few disadvantages in using water as PCM. The most serious problem encountered is the supercooling phenomenon occurring in the water solidification during the thermal storage cooling process.

While the water is cooled in an enclosed container, freezing does not occur at its freezing point (0°C) at atmospheric pressure. Instead, it is normally cooled below 0°C before ice nucleation happens. Supercooled water refers to a state of metastable liquid even though the water temperature is below its freezing temperature. The metastable state will end when ice nucleation occurs and the thin plate-like crystal of dendritic ice grows into the supercooled region of water. During the dendritic ice growth process, latent heat is released from the dendritic ice and consumed by supercooled water. At the end of this initial growth process, normally the temperature of water returns to its freezing point (0°C). If the metastable state exists and remains during the thermal storage process, thermal energy can only be stored in the form of sensible energy. In this case, the storage capacity is strongly reduced. There are several studies about solidification of water; Chen et al. (1998) studied the numerical and experimental method to analyze the influence of nucleation agents in the water solidification process inside cylindrical copper capsules of different sizes. Yoon et al. (2001) studied experimentally the freezing phenomenon of saturated water within the supercooled region in a horizontal circular cylinder using the holographic real time interferometry technique. Milón and Braga (2003) studied the phenomenon of supercooling in spherical capsules of different diameters and determined the parameters that influence this phenomenon appearance. Okawa et al (2001) studied a freezing of supercooled water on a metallic plate. Gilpin (1977) studied the dendritic ice form in a pipe during the freezing process. It has been show that growth of dendritic ice can cause blockage of the water pipe. The extent of dendritic growth is largely determined by the temperature distribution that exists in the pipe at the time of ice nucleation.

In the literature two types of ice blockage are cited: a blockage of the pipe cross section by dendritic ice forming, as result of supercooling in the water, and a subsequent blockage of the pipe by the growth of a solid annulus of ice from the pipe wall. Small diameter pipes are much more likely to be blocked by dendritic ice than large pipes. The slower the cooling rate that the pipes are exposed to the more likely it is to be blocked by dendritic ice. At high cooling rates only the water near the pipe wall, primarily the top of the pipe, experiences the supercooling.
The present work studies experimentally the dendritic ice growth in supercooled water inside cylindrical capsule with perfectly geometry made from acrylic.

2. EXPERIMENTAL APPARATUS

The experimental apparatus, shown schematically in Figure 1, consists in a test section (a), an observing system (b), a cooling system (c), and a measurement and data acquisition system (d).

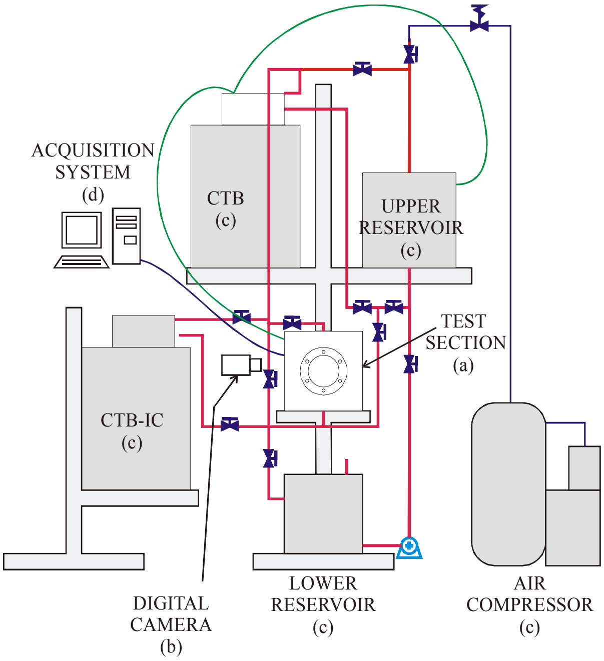

Figure 1: Experimental apparatus schematic diagram: test section (a); observing system (b); cooling system (c) and acquisition and measurement system (d).

2.1. Test section.

This section contains the capsule to be analyzed. The walls are made of a 10 mm thick acrylic plate externally covered with a 25 mm thick insulation. A cross section of the test section is shown in the Figure 2. The diffuser is intended to homogenize the coolant temperature (TC) in the test section. The temperature control is carried out by a constant temperature bath which receives the signals from a temperature sensor RTD type PT-100. K type thermocouples were used for the circulating fluid temperatures registration. Two flanges are installed in the vertical walls to facilitate the capsule installation. An overflow tank, working at atmospheric pressure, was installed to compensate the volume variation during the phase change process. In the same figure, the cylindrical capsule, filled with the PCM (distilled pure water), can be observed. To define the volume of the PCM, a sliding disk (movable in the axial direction) is used. K type thermocouples of 0,076 mm diameter, covered with Teflon, are also indicated.

2.2. Observing system

A digital camera (30 images per second), located inside an extern container, is used to register the exact instant of the nucleation and the growth of the ice (Figure 2). To avoid condensation, the space between the capsule and the camera’s lens is filled with nitrogen, inert gas that removes the humid air. The box is also insulated.

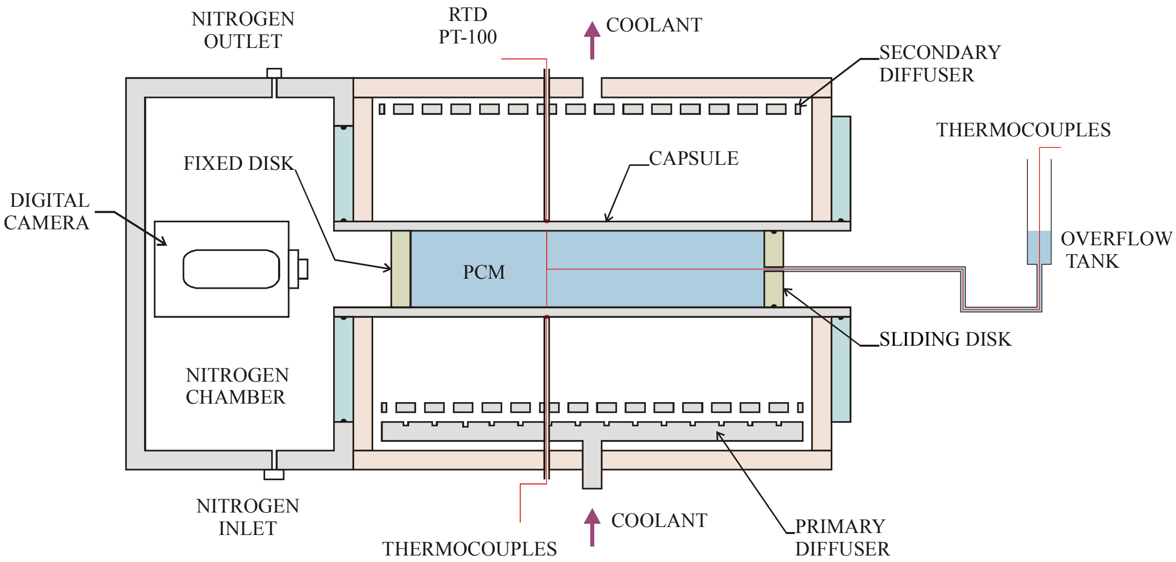

Fig: 2. Test section details.

2.2. Cooling system

The cooling system is schematically showed in Figure 1. It is composed by two constant temperature baths (CTB), two reservoirs (upper and lower) and the coolant. The initial temperature for the tests is set at one CTB-IC while the other CTB is set at the test temperature. The temperature control system is of the PID type (Proportional Integral Derivative) and it is able to maintain the temperature into a range of ±0.05 °C with a refrigeration power of 800 W at 0 ºC and 1000 W of electric power heater. The coolant is an alcohol-water solution (50% in volume).

2.3. Measuring and data logging system

The measurements and storage of data are made by the data acquisition system and a personal computer (PC). The acquisition equipment, which communicates with the PC by the RS232 communication port, receives, processes and transmits the temperature signals to PC, for storage and posterior analysis.

3. EXPERIMENTAL PROCEDURE

Stage I: The initial water temperature inside the capsule (25.0 ºC) is imposed using the constant temperature bath for the initial condition (CTB-IC). The other CTB controls the coolant temperature in the upper reservoir.
Stage II: The coolant of the upper reservoir pass through the tests section imposing the test temperature, absorbing the initial thermal loads and passing later to the lower reservoir.
Stage III: The coolant of the CTB is addressed toward the test section until the conclusion of the test.
Stage IV: After each test, a pump impels the coolant toward the upper reservoir for a new test.
This procedure is carried out to maintain constant the test temperature along each test. The duration of each test varies from 30 to 60 minutes, depending of the test conditions. The data is acquired once a second. Uncertainties are presented in Table 1.

Table 1: Uncertainties of measurements

Parameter	Uncertainty
Temperature	0,1 ºC
Time	0,01 s
Length	0,01 mm

3.1. Investigated parameters

The following parameters were investigated: dendritic ice growth and temperature inside the cylindrical capsules made of acrylic. The capsule has a 45 mm internal diameter and 1.5 mm wall thickness. Experiences were carried out with different temperatures of the coolant (T_C= -6, -8, -10, -12, -14, -16 and -18 ºC).

4. RESULTS AND DISCUSSION

In Figure 3, it is possible to observe the case for the acrylic capsule with T_C = -16 ºC. When the nucleation process happens, part of the PCM is supercooled (see temperatures from thermocouples 2, 3, 4, 5 and 8) while the center-bottom region of the capsule (thermocouples 6, 7 and 9) is above of T_f (0ºC). During the nucleation process, the latent heat released by the phase change increases the temperature of the surrounding reminiscent liquid to the phase change temperature. In some cases (see for example the thermocouple 2), after the nucleation the temperatures increases over the phase change temperature (T_f). This happens, probably, due to the advection of the reminiscent liquid that is pushed by the increasing of the volume of the formed solid. In this case, the "blockage" for dendritic ice growth is partial. This concept of blockade was introduced by Gilpin (1977).

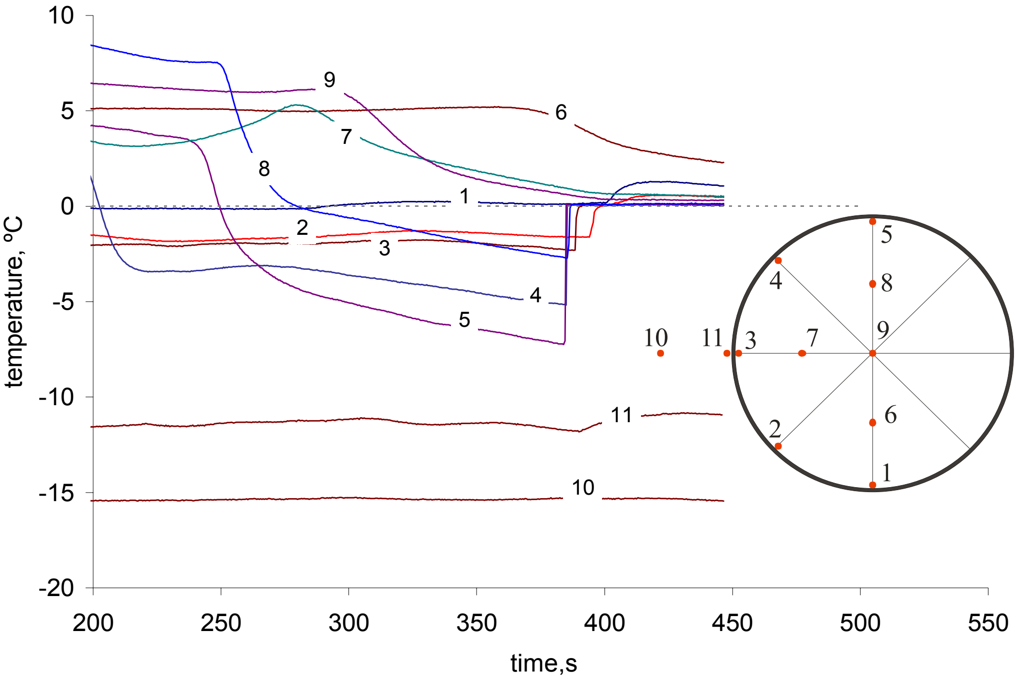

Figure 3: Nucleation process: temperatures at different positions inside the acrylic capsule with T_C = -16 ºC

In Figure 4, processed pictures and temperatures for different thermocouples positions are shown for different instants of time. The process of partial blockage for dendritic ice growth happens in approximately 22 seconds.

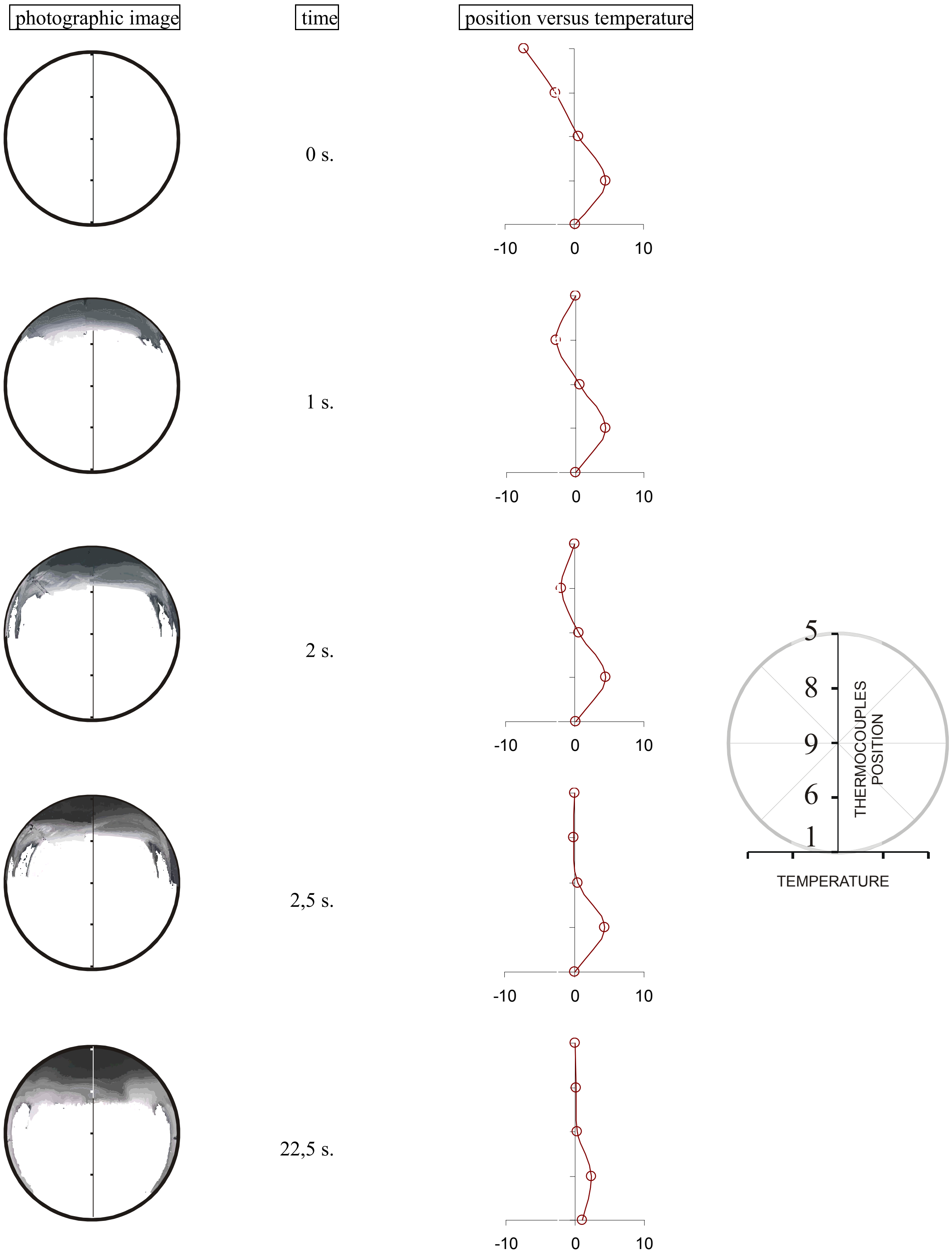

Figure 4: The dendritic ice growth and the temperature profile along a vertical section through the capsule at various instants of time during the dendritic ice growth. Acrylic capsule with T_C = -16 ºC

The case for the acrylic capsule with T_C = -12 ºC is shown in Figure 5. It can be noted that, in this in case, the entire volume of the PCM is supercooled when the nucleation happens. Although the coolant temperature is higher in this case, when compared with the previous one, the nucleation process occurs after more than 800 seconds of cooling period, that is more than two times greater than the previous period. The blockage for dendritic ice growth here is total (see Figure 6) and takes only 6 seconds to be completed.

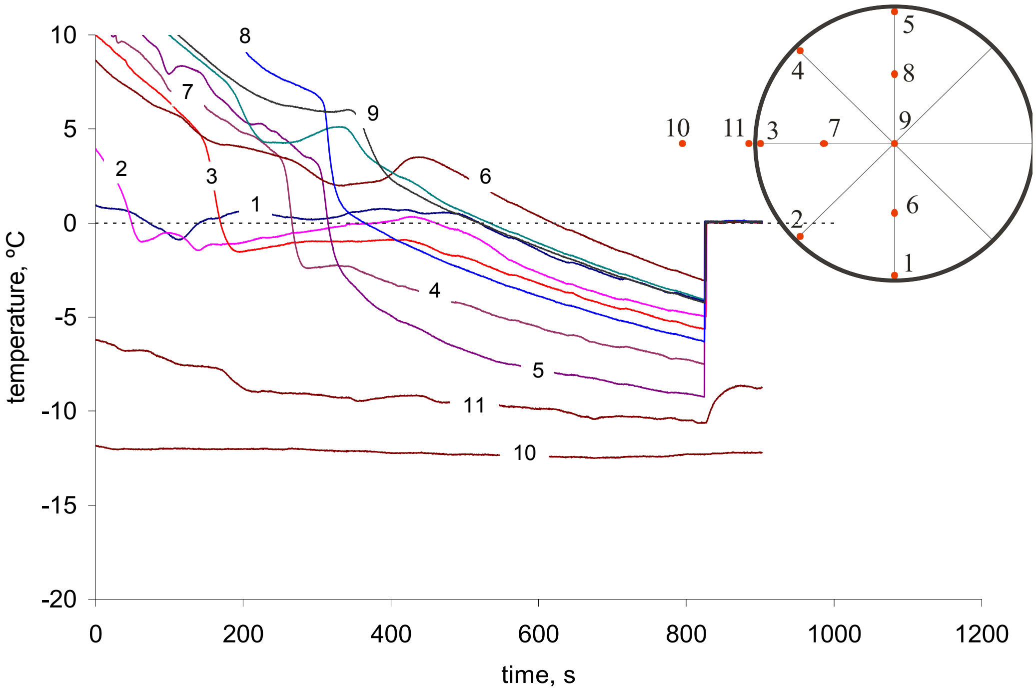

Figure 5: Process of nucleation, different positions of the thermocouples. Acrylic with T_{FT} = -12 ºC

It is important to stand out that the nucleation time, defined as the period of time while the fluid remains supercooled, is different from the time of dendritic ice growth, that happens after the nucleation process, when the temperatures the PCM return to T_f . After the nucleation process the dendritic ice growth continues.

The time of blockage for dendritic ice growth is shown in Figure 7. It is possible to observe there that, when T_C is low, the time of blockage for dendritic ice growth is large, and vice verse. As low as the coolant temperature is, less time is necessary until the nucleation process takes place. Because of this, less part of the fluid is supercooled and the dendritic growth is slower.

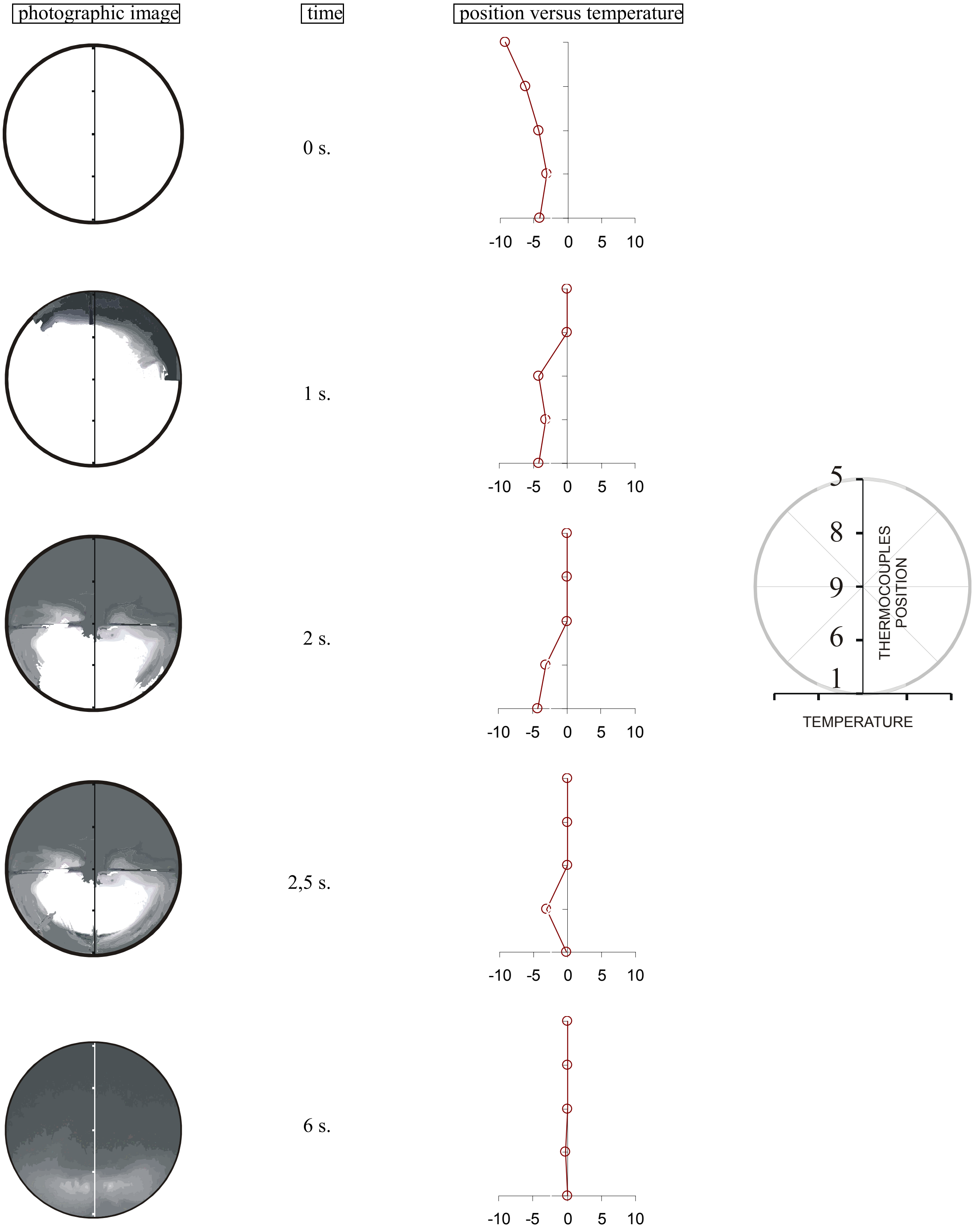

Figure 6: The dendritic ice growth and the temperature profile along a vertical section through the capsule at various instants of times during the dendritic ice growth phase. Acrylic capsule with T_{FT} = -12 ºC

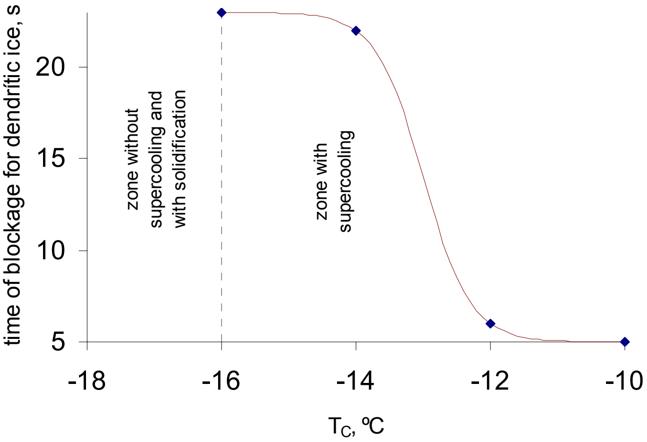

Figure 7: Time of blockage for dendritic ice growth for different T_C, acrylic capsule, 45 mm

6. CONCLUSIONS

The blockage for dendritic ice growth is dependent of the coolant temperature and their manifestation depends of the statistical parameters of nucleation and supercooling phenomenon. When the nucleation happens, for lowers T_C, the time of blockage for dendritic ice growth is large, and for bigger values of the T_C, the time of blockage for dendritic ice growth is smaller. The dendritic ice appears only in supercooled region of the water.
When the coolant temperature is too low, no supercooling occurs. The solidification happens with a smooth interface and no dendrites were observed. For the acrylic capsules with 45 mm diameter, this phenomenon occurs for temperature below -16ºC.

NOMENCLATURE

T_C	coolant temperature, [ºC]
Ti	initial temperature, [ºC]
T_f	freezing temperature, [ºC]
PCM	phase change material
CTB	constant temperature bath
CTB-IC	constant temperature bath of initial conditions of the PCM

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