ISSN 1392–1207. MECHANIKA. 2022 Volume 28(6): 439–446

Experimental Investigation of Thermal and Humidity Dynamics in the Enclosures Made of Non-Permeable Walls

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crossref http://dx.doi.org/10.5755/j02.mech.32240

1. Introduction

Electronics devices are widely used in outdoor applications, such as automotive industry, wind turbines, solar panels etc. Consequently, electronics exposure to a harsh environment may lead to a reliability issues due to uncontrolled humidity inside electronics enclosures [1 - 3]. The presence of moisture in electronics can also alter the material properties [4 - 11]. As a consequence, the reliability is one of the most important factors which ensures safe and efficient operation of electronics. The humidity inside electronics is very dependent on the ambient and operating conditions. So, the geographical location and the location of electronics in a complex system is a crucial factor when designing electronics [6]. For instance, the electronics may have a very different conditions when it is placed near to an engine or in the interior of the car. To ensure the optimal operating regime and protection of the electronics devices from the ambient environment, the electronics are placed in the enclosure made of polymeric or metallic materials. Usually, the enclosures do not guarantee the entire protection of the devices from moist air even though an enclosure with high IP classification is selected. The main drawback is that the enclosure is not perfectly sealed thermodynamic system and there is always the heat and humidity transfer caused by the temperature and absolute humidity gradients between the ambient and enclosure ‘s internal climate [8]. Moreover, the polymeric materials are also permeable for water vapour [4 - 11].

A combined complex heat and mass transfer processes occurring in the electronics enclosures are determined by the interaction of heat transfer, water vapour transport by diffusion and convection, phase change of water vapour and condensed water, freezing and melting mechanisms. These mechanisms are very dependent on each other and their interaction influences the intensity of each process. To understand the humidity behaviour inside the enclosure, it is very important to consider an experiment, which could determine the intensity of each mechanism and the interaction between aforementioned mechanisms. Such experiments are also very useful when it needs to predict the humidity using the modelling tools. Another important factor is the selection of an appropriate boundary conditions which may ensure a possible evaluation of every occurring mechanism.

There are a number of moisture paths into electronics enclosures which has an effect for moisture build-up [3], [4]. One of the predominant moisture paths is the enclosure walls made of polymeric material, as it is subject to absorb water vapour [5 - 10]. So, the elimination of water vapour through the walls reduces one of the moisture paths into the enclosure [9] and allows better evaluation of other factors to moisture behaviour. For this purpose, an enclosure made of metal or glass can be used.

Some studies were performed at the enclosure level, wherein the main concern was to analyse the humidity build-up under non-isothermal conditions keeping the temperature above zero [4 - 9]. Thus, there is also a lack of humidity studies inside electronics enclosures which considers the heat transfer processes with the interaction of humidity and the phase change processes below zero Celsius.

Thus, the objective of the paper is to study the temperature and humidity dynamics inside electronics enclosures when enclosures are exposed to varying temperature from 60 °C to -30 °C according to MIL-STD-810F standard. An aluminium and glass enclosures are used for the study of humidity and thermal dynamics. During different temperature regimes, heat transfer and a possible condensation, evaporation, and sublimation processes were analysed.

2. Experiment and theory

2.1. Experimental methodology

To study the humidity and thermal dynamics inside the enclosures, an experiment was conducted in the climatic chamber. Two enclosures with non-permeable walls for water vapour were selected, namely, Fibox Euronord Aln 232011 made of aluminium material and glass jar - made of ordinary glass. The volume of aluminium enclosure was 3,4 litres, while glass jar - 4.225 litre. Enclosures with non-permeable walls are selected on purpose so that a number of moisture paths are limited to a minimum. This allows to simplify the case for the humidity study. Moreover, two different materials of enclosure are used to analysis the effect of different thermal conductivity for the humidity and thermal dynamics. Basically, the experimental setup is very similar to the one used in the previous study [9]. Here, the same two enclosures were analysed as in paper [9], however exposed to a different temperature cycle.

To study the condensation and evaporation, freezing and melting processes and the humidity behaviour, both enclosures are exposed to a temperature cycling depicted in Fig. 2. The temperature cycling is based on the MIL-STD-

810 F standard and goes from positive to a negative and to a positive temperature again. This standard is mostly applied to test the temperature effect in the materials used for electronics devices. In this case, it was important to study the temperature dynamics, the humidity behaviour and phase change processes occurring inside the enclosures under different temperature regimes. Considering the elimination of water vapour transport through the walls of enclosure, the complex heat and mass transfer processes are defined by the heat conduction via walls, convective heat and water vapour transport outside and inside the enclosure and phase change processes in Fig. 2. Phase change processes cover condensation and evaporation, freezing and melting. When the temperature is close to the dew point, a liquid film condensation may occur on the surface of a wall and depending on the conditions, a volumetric condensation can also form. Under negative temperature, ice or snow can form if there is a condensed water. To understand the humidity behaviour inside enclosure, the different temperature regimes were simulated in the climatic chamber to cause the condensation when there is cooling up to 0 °C and freezing under temperature below zero. For melting of a possible ice and evaporation of condensed water, the heating regime is considered.

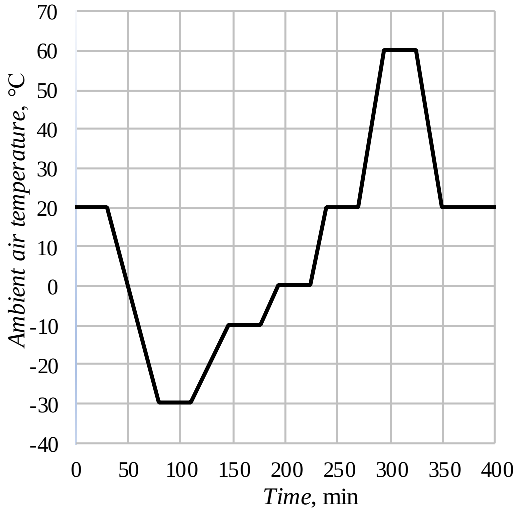


Fig. 1 Theoretical temperature dynamics of ambient air used for climatic chamber

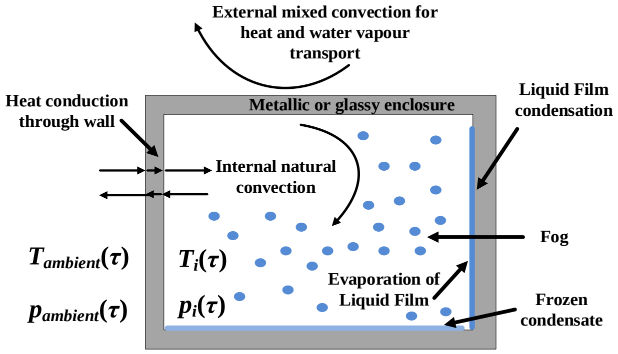


Fig. 2 Illustration of the simplified case for study (air filled enclosure)

The relative humidity (RH) and temperature were measured at different locations of the enclosure as depicted in Fig. 3. The relative humidity sensors from Honeywell HIH 4020 were placed in the centre of the air of both enclosures. The temperature measurements were conducted using T type thermocouples in the centre of air, on the surface of the side wall, at the lid and at the bottom. The measurement readings were captured every 1 minute using Pico-Logger TC-08. The accuracy of experiment is determined by measuring devices. The thermocouple has the accuracy of ±0.5°C while relative humidity sensor is about ± 3.5 % RH.

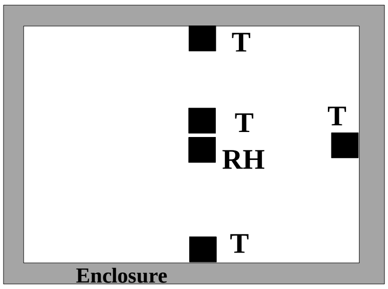


Fig. 3 The sensors position in the enclosure

2.2. Theoretical basis

To process the experimental results, the heat transfer equations and the equations for calculating the humidity related parameters are presented in this section.

The partial pressure of water vapour is important factor used to define the absolute humidity in the enclosure. The partial pressure of water vapour is given according to the measured air relative humidity and the measured air temperature as follows [12]:

$$p_v = \frac{RH}{100\%}\, p_s\left(t_a\right). \tag{1}$$

The saturation vapour pressure in Eq. (1) is given as follows [13]:

$$p_s(t_a) = 610.94\ e^{\left(\frac{17,625\ t_a}{t_a+243.12}\right)}, \tag{2}$$

where: p_s is the saturation water vapour pressure dependent on the air temperature, Pa; RH is the relative humidity, %; p_v is the partial water vapour pressure in the air, Pa. The saturation water pressure is calculated using August Roche Magnus formula.

The dew point temperature is estimated [14]:

$$t_{Dp}(t_a, RH) = \frac{243,12\left(ln\left(\frac{RH}{100}\right)+\frac{17,625\ t_a}{243,12+t_a}\right)}{17,625-\left(ln\left(\frac{RH}{100}\right)+\frac{17,625\ t_a}{243,12+t_a}\right)}, \tag{3}$$

where t_a is the temperature of the air, °C; t_{Dp} is the dew point temperature, °C.

The heat transfer processes between surrounding environment and the air inside an enclosure occurs through the wall. The driving force of the heat transfer (flow) depends on the temperature difference Δt_a between the surrounding air t_{a2} and the air inside an enclosure t_{a1}. Thus, the heat flow is directly proportional to a temperature difference and surface area of a wall, however inversely proportional to a thermal resistance of a wall [12]:

$$Q = A\frac{t_{a2}-t_{a1}}{R} = A\frac{\Delta t_a}{R}, \tag{4}$$

where: Q is the heat flow perpendicular through the surface of the area A, W; t is the temperature, °C; A is the area of the surface, m^2; R is the thermal resistance, m^{2}K/W.

Thermal resistance R defines the thermal conductive resistance R_w, exterior and interior convective thermal resistances R_2 R_1, respectively. The convective heat transfer resistance is inversely proportional to a convective heat transfer coefficient, α, W/(m^{2}K). Thermal conductive resistance is defined as a ratio of wall thickness δ_w, m and material 's thermal conductivity λ_w, W/(m·K). In general, the wall may be comprised of several different wall layers or covered by the layer of film condensation or ice. Thus, the total thermal resistance is defined as the sum of thermal conductive resistances of all wall layers R_{wi} and the convective heat transfer resistances R_2 and R_1 [12, 15]:

$$R = R_2 + \sum_i R_{wi} + R_1 = \frac{1}{\alpha_2} + \sum_i \frac{\delta_{wi}}{\lambda_{wi}} + \frac{1}{\alpha_1}. \qquad (5)$$

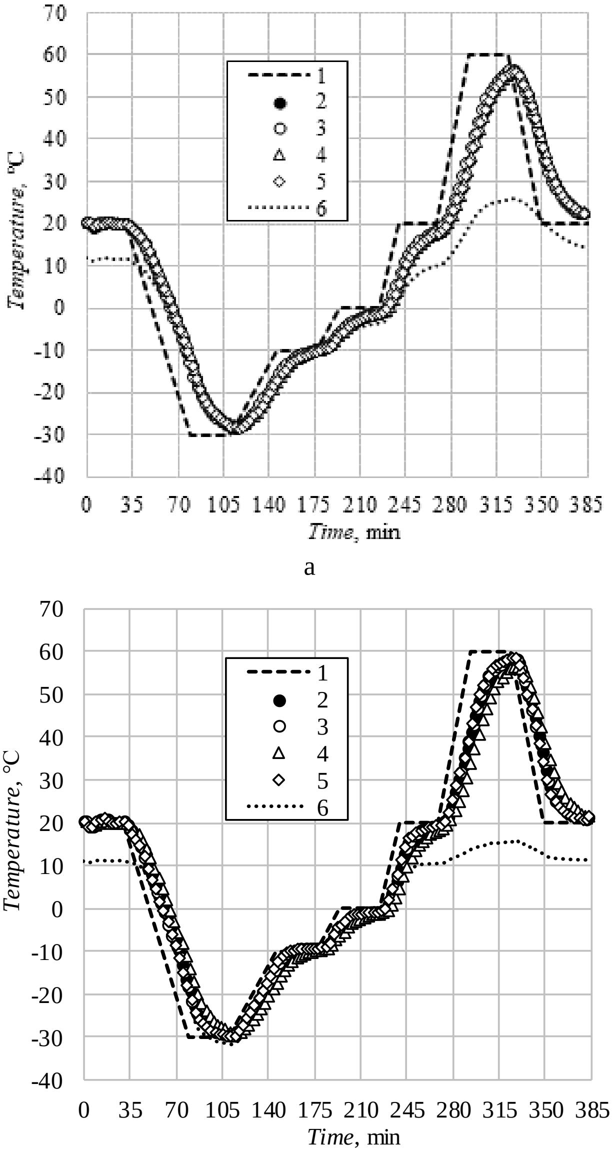
The temperature field distribution is dependent on the thermal resistances of each wall layer and convective thermal resistances. The temperature of exterior t_{w2} and interior t_{w1} wall surfaces is dependent on convective thermal resistances. The internal convective heat transfer occurs due to a natural convection mechanism, while exterior heat transfer outside the enclosure is determined by the mixture of natural and forced convection.

3. Experimental results and discussion

The experiment was carried out in the climatic chamber when the ambient temperature changes according to Fig. 2. The initial temperature in the air of aluminium enclosure and glass jar were 20°C, while the initial relative humidity in aluminium enclosure was 55,95% and in glass jar – 59,78%. Depending on the temperature levels, the different mechanisms are expected to observe. Three temperature regimes can be distinguished in the applied theoretical temperature cycle (Fig. 2).

In the first 110 min interval of cooling regime, the ambient air at 20°C is cooled down to -30°C in both electronics boxes (Fig. 4). This cooling mode includes the stabilization periods of 35 min for the initial temperature of the air and the cooled air. In the second 210 min long heating regime, the ambient air is heated to a temperature of 60°C (Fig. 4. curve *1*). The air inside both boxes does not have time to warm up to this temperature (60°C) by approximately 2°C in the glass enclosure (Fig. 4, a curve *2*) and about 1°C in the aluminium enclosure (Fig. 4, b curve *2*). In the heating regime four ambient air temperature (-10°C, 0°C, 20°C and approximately 60°C) stabilization periods of 35 min are included. After this the ambient air is cooled down to the former initial temperature of 20°C in the third 70 min long cooling regime. Final stabilization period of 35 min take place for the thermal state corresponding to the initial temperature of 20°C to be established in both the aluminium (Fig. 4, a curves *2*-*5*) and glass (Fig. 4, b curves *2*-*5*) enclosures.

Dynamics of the measured relative humidity is very important in the electronics enclosures and according to it, the temperature variation of the dew point t_{Dp} is calculated. The discrepancy between the dew point temperature $t_{Dp,\infty}$ at the end of the experiment and the dew point temperature $t_{Dp,0}$ at the beginning of the experiment defines inflow/outflow of water vapour through the tested electronics enclosures, since the flow through the walls is negated in aluminium and glass enclosures. In the glass enclosure, the conditions for inflow/outflow of water vapour through the gasket are unfavourable, because the rubber gasket is relatively small and is tightly covered by the metal cover. Therefore, the dew point temperature in the air of glass enclosure at the beginning and the end of the experiment practically does not differ and is approximately 11°C (Fig. 4, b curve *6*).

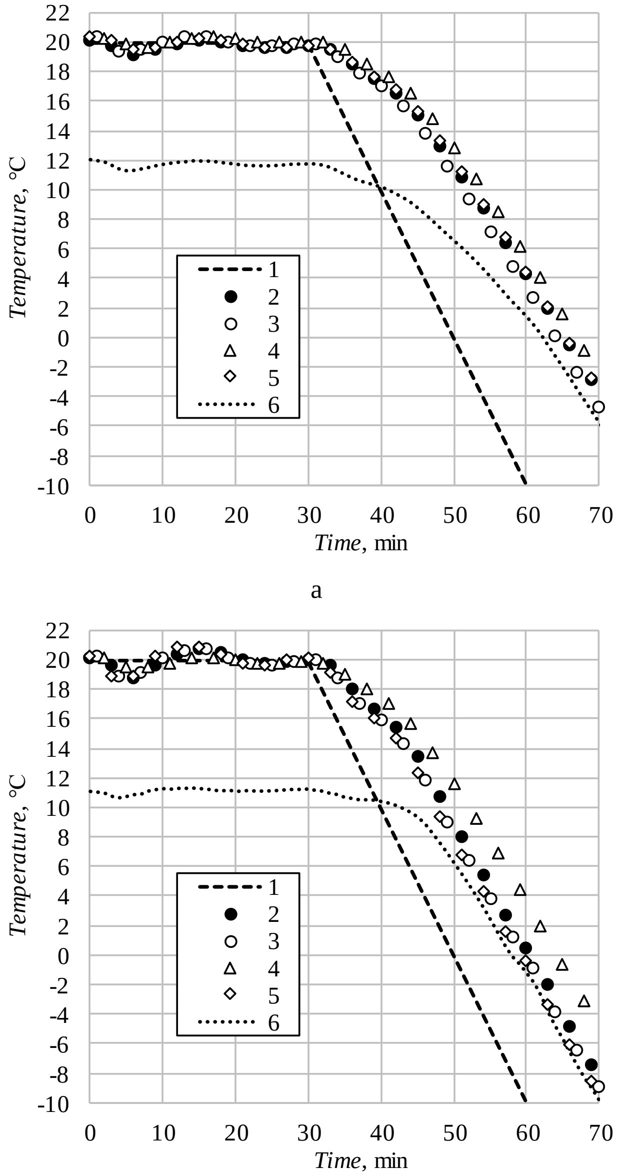


a

b

Fig. 4 Dynamics of the thermal state in the glass (a) and aluminium (b) enclosures: *1* - applied air temperature of the climate chamber; *2* - measured air temperature in the centre of the enclosures; *3* - measured temperature of the inner surface of the side wall; *4* - measured temperature of the inner surface of the bottom; *5* - measured temperature of the inner surface of the lid; *6* - calculated dew point temperature

Meanwhile, in the aluminium enclosure, the dew point temperature $t_{Dp,\infty}$ at the end of the experiment is approximately higher by 3°C than the temperature $t_{Dp,0}$ (Fig. 4, a curve *6*). This confirms that the inflow of water vapour through the gaskets of aluminium enclosure can have a significant influence on the microclimate during electronics operational usage or storage (this observation also applies to widely applicable plastic enclosures, where the inflow/outflow of water vapour through conductive walls will additionally have an effect).



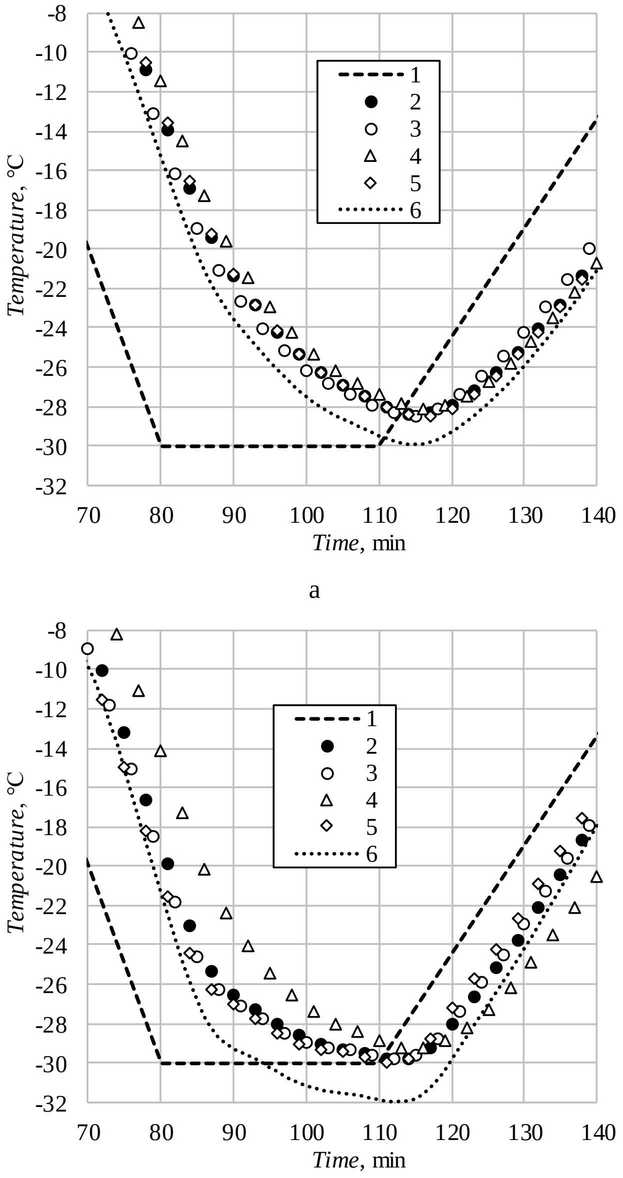
a

b

Fig. 5 Dynamics of the thermal state in the glass (a) and aluminium (b) enclosures under steady state conditions and the first cooling regime. The same markings as in Fig. 4

The actual temperature of the ambient air in the climate chamber will differ from the theoretical one (it will be a little higher in the cooling mode, and a little lower in the heating mode). It goes without saying that the temperature variation of the air will be even more inert in the box. Therefore, for the comparative evaluation, the periods of stabilization of the thermal state are very important, since the complex operational conditions defined by the MIL-STD-810F standard were maintained in the conducted experiments.

The boundary conditions of the heat exchange process of the side walls, bottom and lid of a flat geometry electronics enclosure are specific. These conditions, at the bottom and the lid of the box, are defined by the warmed up and cooled air and its movement.



a

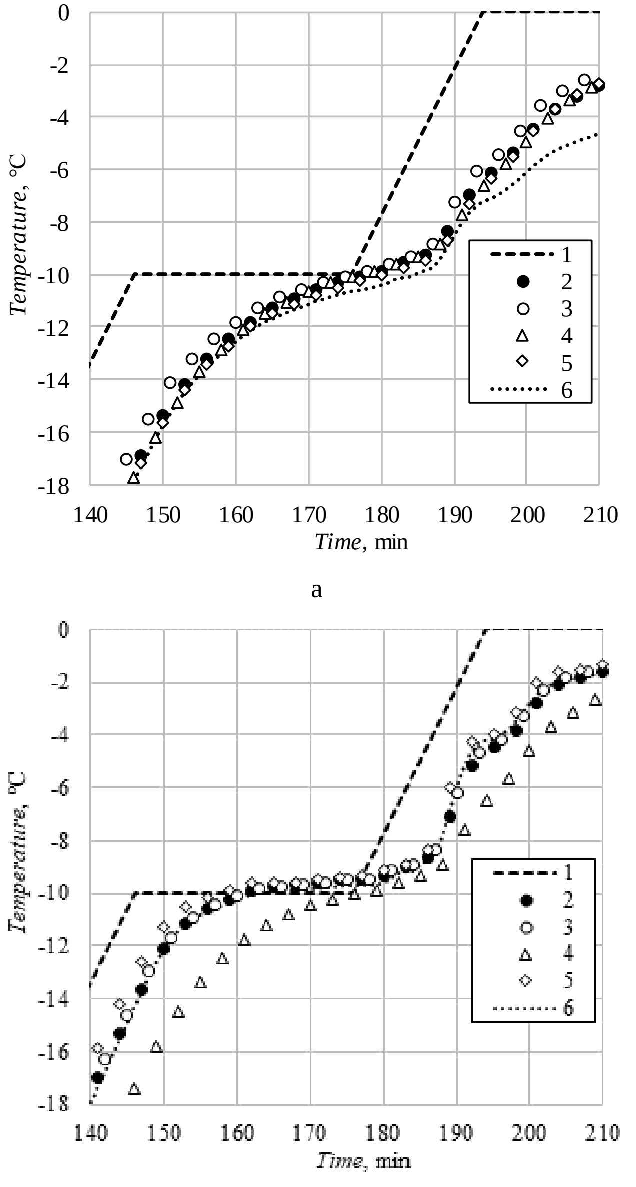
b

Fig. 6 Dynamics of the thermal state in the glass (a) and aluminium (b) enclosures during the transition period from cooling to heating mode. The same markings as in Fig. 4

In the cooling mode of the box, the cooled air at the side walls and the lid descends freely under free convection. Meanwhile, the cooled air at the bottom of the box cannot descend, so an increasing layer of lower temperature air accumulates at the bottom. This creates a prerequisite of the thermal resistance increase at the bottom.

The heated air near the side walls and the bottom rises freely by free convection in the heating mode of the box. The heated air near the lid of the box cannot rise, so an increasing layer of higher temperature air accumulates near the lid. This creates a prerequisite of the thermal resistance increase at the top.

Thus, the thermal resistance of the heat transfer process through the walls of the enclosure changes differently and therefore the temperature dynamics of their surfaces are unique. In this research the thermal state of air in the enclosure is determined by instantaneous air temperature measured at the centre of the enclosure (Fig. 4 curve *2*). The thermal state of the walls is defined by the instantaneous temperature of the inner surface of the side and is measured at their centres (Fig. 4 curve *3*). The instantaneous temperatures of inner surface of the bottom (Fig. 4 curve *4*) and the lid (Fig. 4 curve *5*) are also measured. There is a specific change of thermal state of the air and the enclosure partitions at different heating and cooling regimes Fig. (5-9). Experimental thermograms reveal several important factors defining the microclimate in electronics enclosures.

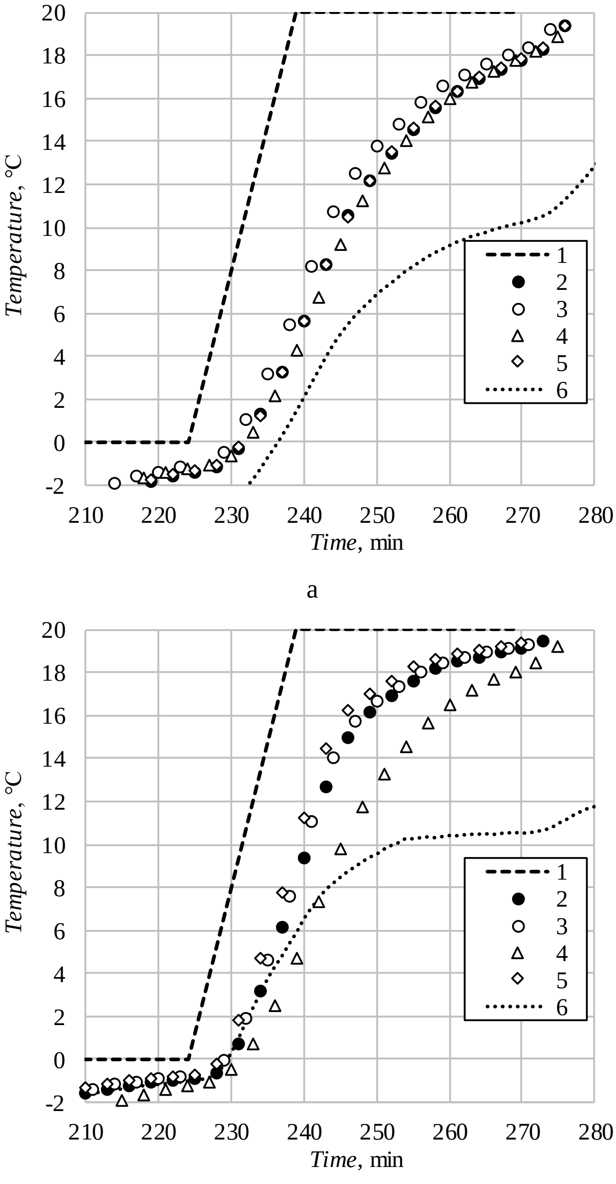


a

b

Fig. 7 Dynamics of the thermal state in the glass (a) and aluminium (b) enclosures in the first heating regime. The same markings as in Fig. 4

In fact, the material of the enclosure walls, that defines the thermal conductive resistance, has a clear influence on the air temperature dynamics inside the enclosure and on the enclosure walls. The thermal resistance of the glass wall compared to the aluminium wall is high and therefore weakens the influence of external and internal heat transfer processes. In addition, the surface area of the metal cap of glass enclosure is relatively small. Therefore, the dynamics of the temperature change of the individual partitions of the glass enclosure are close and the experimental points are located quite closely (Figs. 5-9, a). The variation in the temperature of the walls of the aluminium enclosure is not uniform. The temperature dynamics at the enclosure bottom (Figs. 5-9, b curve *4*) stand out particularly. It is significantly slower during both cooling (Figs. 5, b; 9, b curve *4*) and the heating (Figs. 7, b; 8,b curve *4*) regimes. Also, interesting to note that the arrangement of points in the thermograms during the transient regimes, from cooling to heating (Fig. 6) and from heating to cooling (Fig. 9), changes the places in both glass and aluminium enclosures. Thus, the qualitative regularity of the temperature variation in the partitions remains.

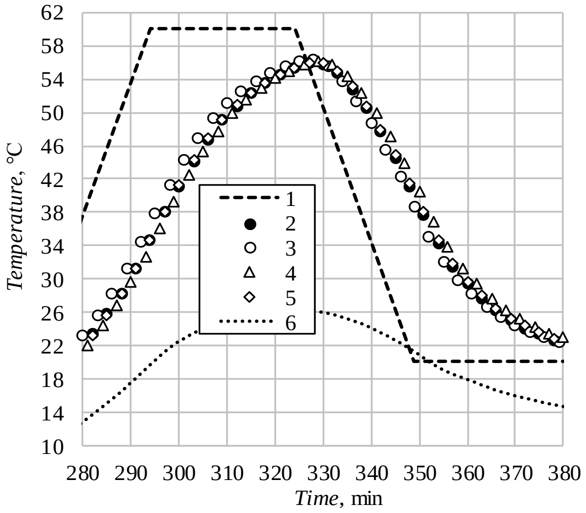


a

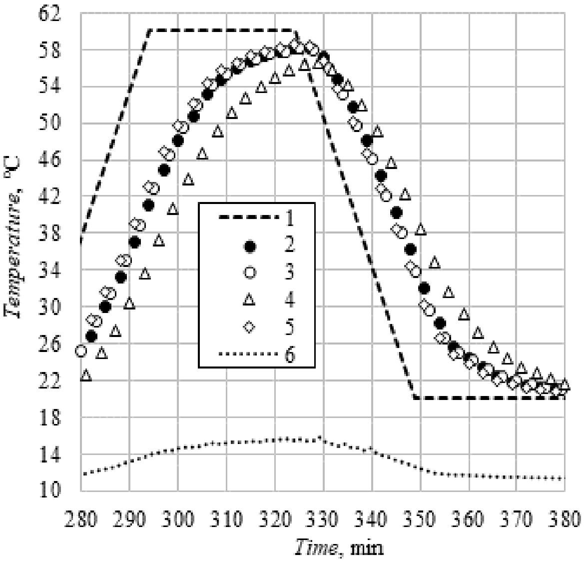
b

Fig. 8 Dynamics of the thermal state in the glass (a) and aluminium (b) enclosures during the second heating regime. The same markings as in Fig. 4

Another important factor is the air temperature inside the enclosure and its walls being very close to the dew point temperature and therefore it creates the conditions for volumetric and surface partial condensation of the vapour in the air. Droplets that are formed in the air or the film of condensate on the inner and outer surfaces of the partitions can freeze into ice when the temperature reaches negative values in the cooling regime. This creates the conditions for the sublimation process to take place, and the ice thawing process will also begin in the heating mode. In the conducted experiment, the humidity of the ambient air was close to humidity of the air in the enclosure. As the surfaces of the enclosure partitions gradually cool down to the dew point temperature, conditions are created for the surface condensation to occur.



a



b

Fig. 9 Dynamics of the thermal state in the glass (a) and aluminium (b) enclosures during the transient and final cooling regime. The same markings as in Fig. 4

The temperatures of the contact layers are determined by the dynamics of the heat flows in them. Since the heat does not accumulate on the surfaces, the instantaneous temperature of the surfaces ensures the balance of the heat flows entering and leaving the surface. If vapour/water/ice phase transformation processes do not take place on the outer and inner surfaces of the walls of the electronics enclosures, the heat flow balance on these surfaces is defined by the processes of heat exchange, convective cooling, heating and heat conduction in the walls. The discussed peculiarity of convection inside the enclosure determines that the temperatures of individual partitions vary in their own way. While in the cooling mode the outer surfaces of the enclosure are cooled faster to the dew point temperature defined by the ambient air parameters. Therefore, when the initial air humidity in the environment and in the enclosure is close, the condensation on the outer surface starts earlier than on the inside.

After the internal surfaces of the enclosure walls cool down to the dew point temperature of the enclosure air, surface condensation of vapour begins, and the prerequisites for volumetric condensation are created even later. When the negative temperature is reached, conditions are created for the condensation film to freeze and the sublimation process to take place. In the heating regime the processes of defrosting and water evaporation occurs inside the enclosure. The ongoing processes of steam/water/ice phase transformations are associated with a significant release or consumption of thermal energy in the phase transformation. Therefore, the processes of phase transformations have a significant contribution to the balance of heat flows at the contact surfaces. Because of the peculiarities mentioned above, the influence of the heat exchange processes weakens, therefore, during the phase transformation processes at certain periods, the temperatures of the separate walls change more evenly. (Figs. 7 and 8).

Condensation is an unwanted and harmful process for electronic devices. To avoid it, it is necessary to artificially dehumidify the air in the electronics enclosure at the beginning of exploitation. This enables the dew point temperature to remain lower than the temperatures of the air and the internal surfaces of the enclosures. Ensuring this is a big challenge, an additional diffuse inflow of vapour through the conductive walls is possible during electronics exploitation. In addition, the necessity to open the enclosures causes significant uncertainty during their exploitation.

An additional consideration has to be considered for the vapour inflow/outflow through the walls of the electronics enclosure that are permeable to vapour diffusion. Thus, the climate inside and outside the electronics enclosures is defined by the set of complex heat and mass transfer processes, which strongly depends on the exploitation conditions of the enclosure. To develop practical recommendations for regulating the climate inside the electronics enclosures, further experimental and theoretical studies of complex transfer processes are needed in a wide range of boundary conditions.

4. Conclusions

The results of the experimental study are summarized as follows:

The climate inside the enclosure is very dependent on the changes of ambient conditions. Reduced ambient temperature may create the conditions for volumetric and surface partial condensation of the water vapour inside the enclosure to occur. In this case, the droplets in the air and film condensation on inner and outer surfaces of the wall will form.

When the negative temperature in the enclosure is reached during the cooling regime, the droplets that formed in the air and the film of condensate on the inner and outer surfaces of the wall can freeze into an ice. The thermal resistances of walls increase distinctively due to uneven formation and distribution of ice and frozen droplets on the wall surfaces. Differently increased thermal resistances change the temperature field in the walls and therefore the sublimation process may occur. This has also a big impact for the changes of humidity and temperature inside the enclosures.

In the heating regime, the ice starts melting into water, which, later on, evaporates and exist in stage of water vapour. Defrosting and evaporation of water determine the increase of water vapour content in the air. Additionally, the humidity is also transported into the enclosure from the ambient due to increased temperature and diffusion process via gaskets and cable feedthrough.

When the phase transition processes do not occur during heating and cooling regimes, the thermal state of enclosure walls is defined by the distinctive heating or cooling airflow dynamics around the enclosure which causes different internal heat convective transfer.

Thus, it is very needed to develop means for humidity control inside the enclosure. The developed means would ensure a proper microclimate inside the enclosure under different ambient conditions. One of the means could be a good ventilation or absorption of humidity by using a desiccant or drainage.

Acknowledgments

This research is funded by the European Social Fund under the No 09.3.3-LMT-K-712 “Development of Competences of Scientists, other Researchers and Students through Practical Research Activities” measure.

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EXPERIMENTAL INVESTIGATION OF THERMAL AND HUMIDITY DYNAMICS IN THE ENCLOSURES MADE OF NON-PERMEABLE WALLS

Summary

The usage of electronics in outdoor environment is growing and therefore the moisture related failures in electronics are becoming more important. The main cause of these failures is the humidity inside electronics which may condense on the PCBA surfaces or its components. To protect electronics from harsh environment, the components and electronics are encapsulated by using electronics enclosures, however it does not prevent from moisture ingress through plastic walls, gaskets, cable feedthroughs and etc. To control the humidity, it is very important to understand the humidity ingress and behaviour in electronics enclosures. Hence, the paper concerns the study of temperature and moisture dynamics when electronics enclosure is exposed to a cyclic temperature condition according to MIL-STD-810F standard.

Two different enclosures were selected for the experiment, namely, aluminium enclosure and glass jar. The study was carried out in a climatic chamber and the measurements of temperature and relative humidity were performed using sensors. Different effects of enclosure material were considered for humidity ingress. In aluminium enclosure, results showed that the temperature difference between different points is smaller than in case of glass jar. Different temperatures in the enclosures are also determined by different boundary conditions outside the enclosure caused by the climatic chamber.

Keywords: heat and moisture transfer; temperature; relative humidity; electronics enclosures; thermal resistance.

Received August 08, 2022
Accepted November 28, 2022