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Numerical Modelling of Moisture Transport Between Two Enclosures Connected by a Tube

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1. Introduction

The protection of electronics devices from the surrounding harsh environment is necessary, therefore they are enclosed with plastic or metallic enclosures [1 - 4]. The usage of enclosure, however, cannot protect the electronic devices entirely from moisture-related failures as the humidity can get into the enclosures through the plastic walls, gaskets or cable feedthrough [2, 5, 6]. Thereafter, failures may occur due to the condensation of moisture on the PCBA or components caused by uncontrolled interior climate. This behaviour is of increasing importance, since the electronics usage in outdoor environment is expanding, through applications within the automotive industry, the renewable energy sector, etc. The location of the electronics plays an important factor, since they are often mounted nearby the heating or the cooling components in a complex mechanical system, e.g. water pump or water meters [3, 4]. In such applications, the temperature of electronics is affected by the external component temperature, such that a forced temperature gradient is created between the heated active electronics and the cold areas within the system – e.g. the cold water in a pump or water meter tube. Moreover, the electronics is also affected by the surrounding environment, therefore the complex transient heat and mass transfer processes has to be considered. To study these processes, the development of modelling tools is needed, which would allow the prediction of moisture and temperature within the devices and the amount of condensed water vapour in the cold areas. Consequently, these modelling tools may support the early stages of designing the electronics rather than using only experiments at the late stages of the design.

Modelling tools are very important in the electronics design process, because it can save time and are often less expensive compared to experiments. There are several methods used for the development of numerical tools, such as, CFD, FEM or FDM [7 - 9]. The main factor in modelling is the computational time and spatial resolution [11, 12]. High fidelity models based on CFD and FEM are time consuming, while the low fidelity models like those based on thermal circuits and Resistor-Capacitor (RC) approach are faster, albeit with less spatial resolution. The RC approach has been applied in some research studies of humidity and temperature predictions [11 - 14]. These studies showed a good alignment with experiments when simple configuration enclosures are considered under isothermal conditions [15]. Thus, RC approach looks promising for further development and application for a more complex electronics system.

Most of the studies of humidity and temperature predictions were carried out on electronics enclosures [8, 12, 15]. One of the previous study [16] considered the humidity and temperature predictions in the two connected enclosures which were made of glass. The study accounted for the forced thermal gradient imposed between two enclosures, but the ambient conditions were not taken into account. Further, the influence of the plastic material, such as in the typical electronics enclosure, was not investigated. To model the more realistic case, a more extended RC circuits is needed, which may then be applied to analyse the impact of the different climatic conditions and to examine the different materials used for enclosures.

The objective of the paper is to present the numerical modelling of the temperature and humidity in the two connected electronics enclosures based on the Resistor-Capacitor (RC) approach. Numerical modelling is performed using an in-house developed code. Two different materials are considered for the warm enclosure namely, polycarbonate and PBT, while cold area is supposed to be made of metallic material in both cases. The transient heat and mass transfer and condensation processes were considered under B3 STANAG climatic conditions and the heating in the warm enclosure.

2. Methodology and theory

The previous study [16] analysed only the case when two connected enclosures were made of glass. The investigated case in this study is depicted in Fig. 1, and consists of two connected enclosures of polymeric and metallic materials respectively, connected via a tube. One enclosure is labelled as warm and represents the electronics box placed on the pump, while the enclosure labelled as cold corresponds to the cooled region of the pump. Warm enclosure is made of plastic material, however the cold enclosure is metallic. Both enclosures are air-filled. The region labelled as tube contains the connections of the cables between electronics box and pump. The tube is made of ordinary glass, so that there is no absorption of water vapour in the wall and transport via wall. For simplicity, the moisture and heat transport through the insulation of cable connections and the small air gaps in the connections are represented by the air in the tube.

The study concerns forced thermal gradient between two connected enclosures, heating in a warm chamber, the effect of different climatic conditions and different plastic materials for humidity transport.

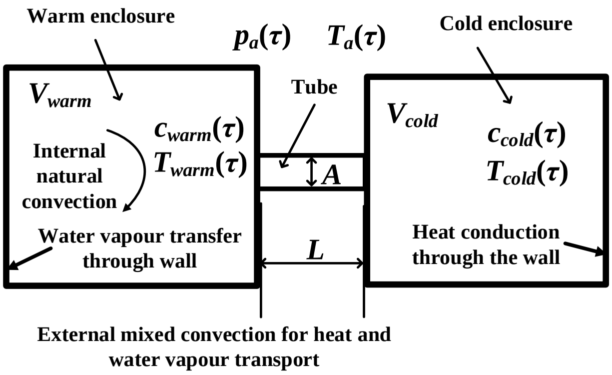


Fig. 1 Two-connected enclosures for temperature and humidity modelling

Thus, the transient heat and mass transfer processes existing in the investigated case are mainly defined by the heat conduction and convection, water vapour convective transport inside and outside the enclosure, diffusion through a wall and condensation mechanism in the cold enclosure.

2.1. Theory for humidity modelling

This section outlines the main theory used for studying the transient heat and mass transfer processes in two connected enclosures. The thermal conductive heat transfer and water vapour transport through a flat wall is described by general heat conduction equation and Fick's second law [17, 20]:

$$\rho c_p \frac{\partial T(\tau,x)}{\partial \tau} = \frac{\partial}{\partial x}\left(\lambda(\tau,x)\frac{\partial T(\tau,x)}{\partial x}\right) + Q_{gen}, \tag{1}$$

$$\frac{\partial c(\tau,x)}{\partial \tau} = \frac{\partial}{\partial x}\left(D\frac{\partial c(\tau,x)}{\partial x}\right), \tag{2}$$

where: x is linear coordinate of a wall, m; τ is time, s; λ is thermal conductivity of a material, W/(m·K); c_p is specific heat of a wall, J/(kg·K); Q_{gen} is internal volumetric heat source, W/(m^3·s); T is the temperature, K, ρ is density, kg/m^3; D is diffusivity, m^2/s; c is water vapour concentration, kg/m^3.

Convective water vapour and heat transfer between a surface of solid material and its surrounding fluid are defined as following [18, 19]:

$$G_m = -\alpha_m (c_{a,\infty} - c_{surf}), \tag{3}$$

$$Q_{conv} = A\alpha(T_f - T_{surf}), \tag{4}$$

where: G_m is the convective vapour flux, kg/s; α_m is convective water vapour transfer coefficient, m/s; c_{surf} is concentration of water vapour in air adjacent to the surface of solid while being in equilibrium with air, kg/m^3; $c_{a,\infty}$ is concentration of water vapour in air far from a solid surface, kg/m^3; A is surface area, m^2; m is the abbreviation of moisture; Q_{conv} is convective heat flux, W/s; α is convective heat transfer coefficient, W/(m^{2}K); T_f is average temperature of a fluid, namely, the air, K; T_{surf} is average temperature of a surface, K.

The mass of water vapour in a defined volume is expressed as follows:

$$M_v = cV. \tag{5}$$

The water vapour concentration is calculated by using ideal gas law equation [17]:

$$c = \frac{p}{R_v T}, \tag{6}$$

where: p_v is partial water vapour pressure in the air, Pa; R_v is gas constant for water vapour, J/(kg·K).

August Roche Magnus formula for saturation water vapour pressure is given as follows [21]:

$$p_s(t_a) = 610.94\ e^{\left(\frac{17{,}625\ t_a}{T+243.12}\right)}. \tag{7}$$

Moreover, the dew point temperature is very important factor which defines the temperature at which the condensation will occur and is derived from the empirical Magnus formula [21]:

$$t_{Dp}(t_a, RH) = \frac{243{,}12\left(\ln\left(\frac{RH}{100}\right) + \frac{17{,}625\ t_a}{243{,}12 + t_a}\right)}{17{,}625 - \left(\ln\left(\frac{RH}{100}\right) + \frac{17{,}625\ t_a}{243{,}12 + t_a}\right)}. \tag{8}$$

Here, the relative humidity is defined [17]:

$$RH = \frac{p_v}{p_s(t_a)} 100\%, \tag{9}$$

where: RH is the relative humidity, %; t_{Dp} is dew point temperature, °C; t_a is the temperature of the air, °C; p_s is saturation water vapour pressure dependent on the temperature, Pa.

2.2. Modelling methodology

To develop a modelling code based on the coupled RC approach for temperature and humidity predictions under non-isothermal conditions, some simplifications and assumptions are made similar to the previous study in [16]:

- The temperature is uniform over the external and internal surfaces of two connected enclosures and in the air.
- The water vapour pressure in the air-filled cavity of two connected enclosures is evenly distributed by the convection.
- External convection supports even distribution of water vapour pressure outside the two connected enclosures.
- Condensation is only considered in the cold chamber.

These assumptions were validated under isothermal conditions and gave a good alignment with the experiments [15]. Furthermore, the assumptions allow the simplification of the mathematical model to a one-dimensional analysis.

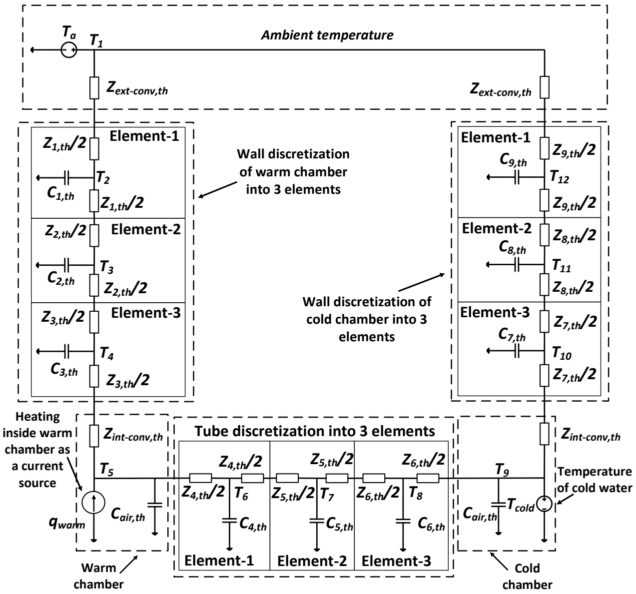


Fig. 2 RC circuit for temperature modelling. *T* denotes the nodal temperature

The RC approach applied in this study is similar to the control volume finite difference method (CV-FDM). To study the humidity and temperature behaviour in the electronics and its enclosures, an RC network consisting of resistors and capacitors is applied. The approach can combine lumped, one-dimensional, two-dimensional analysis of physics, wherein each discretized element is described by the resistance and capacitance.

The modelling of humidity and temperature in the two connected enclosures is based on a coupled RC thermal circuit in Fig. 2 and moisture circuit in Fig. 3. These two different RC circuits combine the lumped and the one-dimensional analysis. Under aforementioned assumptions, lumped components are used to describe the surrounding environment and the air-filled volume of two connected chambers. Here, the surrounding environment is represented by the convective resistance while the air-filled volume is described by the convective resistance and capacitance in both RC circuit. One-dimensional (1-D) description is applied for the wall and the tube connecting two chambers. 1-D description is based on the finite volume method (FVM) discretization and used to solve Fick's second law and the heat conduction equations. The heating of electronics is represented by the heating source in a warm chamber and constant temperature in a cold chamber is defined by the temperature source (Fig. 2). The RC thermal circuit is more complex than the moisture circuit. Since a cold chamber is made of metal, therefore the heat transfer only occurs via walls into surrounding environment and moisture transport is not considered as metal is not permeable for water vapour. Contrary to a cold chamber, warm chamber has plastic wall, therefore the moisture can enter and leave the box.

The wall and the tube are discretized into 3 elements where each element consists of resistors and capacitor. The resistance and capacitance terms for convective and heat transfer in solids in RC thermal circuit are expressed [12]:

$$Z_{i,th} = \frac{\Delta x_i}{A k_i}, \tag{10}$$

$$Z_{th}^{conv} = \frac{1}{hA}, \tag{11}$$

$$c_{i,th} = \Delta x_i (A \rho c_p)_i, \tag{12}$$

where: $Z_{i,th}$ is conductive resistance term, K/W; Z_{th}^{conv} is resistance term, K/W; Δx_i is the space parameter of discretized element, m; *i* denotes the number of discretized element or lumped component; *th* is the abbreviation of thermal; $C_{i,th}$ is capacitance term of particular material, J/K.

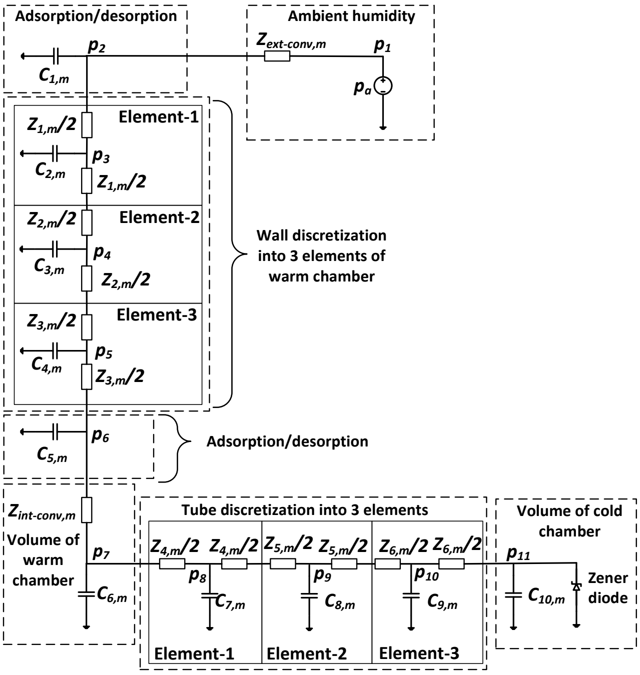


Fig. 3 RC circuit for moisture modelling. *p* denotes the nodal pressure

Since the concentration is not continuous at interfaces of different materials, therefore the partial pressure is used as a driving force. Thus, Henry's law is applied in addition to the Fick's second law equation to enforce the continuity through different materials and its interfaces [12, 22, 23]:

$$c = S(T)p, \tag{13}$$

where: *c* is concentration of water vapour in a solid material, kg/m^3; *S(T)* is temperature dependent solubility coefficient, kg/(m^3·Pa); *p* is water vapour pressure in the air, Pa.

Assuming that the solubility is constant in a bulk material over a time and uniform over diffusing material, the Henry's law inserted into the Fick's second law equation gives the following formulation wherein the pressure is a driving potential:

$$S\frac{\partial p(\tau,x)}{\partial \tau} = \frac{\partial}{\partial x}\left(-DS\frac{\partial p(\tau,x)}{\partial x}\right), \tag{14}$$

Here, the resistance and capacitance terms for solid material in RC moisture circuit are expressed [12]:

$$Z_{i,m} = \frac{\Delta x_i}{P_i A}, \tag{15}$$

$$P = D \cdot S \Rightarrow P_i = D_i \cdot S_i, \tag{16}$$

$$C_{i,m} = V_i \cdot S_i, \tag{17}$$

where: $Z_{i,m}$ is resistance term, s·Pa/kg; P is permeability of water vapour in a solid material, kg/(m·s·Pa); $C_{i,m}$ – capacitance term, kg/m^3.

Inserting eq. (6) into convective vapour transport Eq. (3), the resistance term is given by:

$$Z_m^{conv} = \frac{R_v T}{\alpha_v A}, \tag{18}$$

where: Z_m^{conv} is convective resistance term, s·Pa/kg.

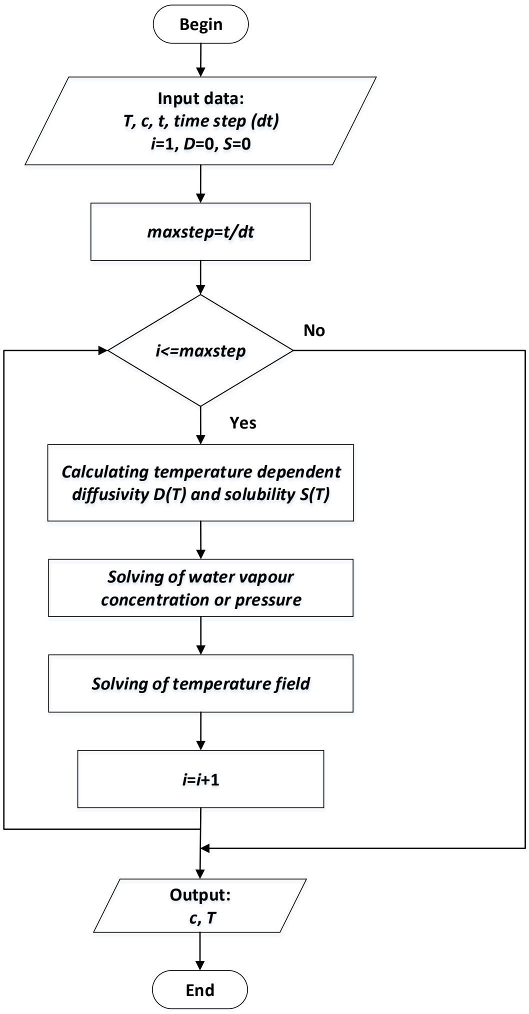


Fig. 4 Algorithm for coupling of RC thermal and moisture circuits

The solubility of water vapour for air is different than for a solid material and its expression is as follows [11]:

$$S(T) = \frac{1}{R_v \cdot T_{air}}. \tag{19}$$

The adsorption and desorption mechanisms are also considered in RC moisture circuit (Fig. 3) and its mechanism is explained in a previous study in paper [12]. To capture the changes of humidity at the surfaces, the adsorption and the desorption phenomena are described by the capacitor outside and inside the two connected enclosures. In this case, the thickness of wall surface is supposed to be 0,1 mm and the adsorption and desorption are considered even [12].

To study the accumulated mass of water vapour in a cold chamber, the condensation process is represented by the Zener diode in RC moisture circuit. Basically, the mass of accumulated water vapour is calculated by the following equation:

$$M_{condensed} = (c_{cold} - c_{sat}(T))V_{cold}, \tag{20}$$

where: $M_{condensed}$ is the condensed water vapour, kg; V_{cold} is the volume of cold enclosure, m^3; c_{cold} is the concentration of water vapour in the cold enclosure, kg/m^3; c_{sat} is the temperature dependent concentration of water vapour in a cold enclosure at saturation level, kg/m^3. The saturation concentration can be estimated using Eq. (7) and the ideal gas law. A detailed algorithm of calculating the condensed water vapour in a cold enclosure was discussed in paper [16].

To simulate the heat transfer and water vapour transport in two connected chambers, coupling of RC thermal and moisture circuits is implemented based on the algorithm depicted in Fig. 4. In fact, the temperature dependent solubility and diffusivity are used to couple these circuits, so that the temperature of each node from RC thermal circuit is an input for moisture circuit's nodal point. Each nodal temperature changes the solubility and diffusivity which in turn alter the properties of materials for moisture transport and influences the entire moisture transport.

The developed code is solved in Matlab using modified nodal analysis scheme [24] with implicit solver (Backward differentiation integration method) [18]. The calculation is completed if 10^{-6} condition is met between two calculation iterations. This allows to achieve the calculation uncertainty of 0,5 % for the humidity and 0,1% for the temperature.

3. Modelling results and discussion

For the investigated case, the modelled two-chamber enclosure is exposed to an oscillating relative humidity (RH) and temperature condition based on B3 STANAG ambient conditions (Fig. 5) [25]. These conditions correspond to the humid hot coastal desert areas such as the Persian Gulf and Red sea. The warm and cold enclosures have the same volume of 392,69 cm^3. The tube has a length of 4,6 cm and diameter of 1,6 cm. The wall thickness of both enclosure is supposed to be about 3 mm. The relative humidity in both enclosures is initially at 40 %, while temperature is of 25 °C. When the process starts, the temperature inside cold chamber was equal to 4 °C constantly and corresponds to the cold water of a working pump. The modelling was performed with two different plastic materials for the wall of the warm chamber, namely, polycarbonate and PBT-30 GF materials. These materials are selected to analyze their effect for moisture transport and the accumulated mass of water. The properties of these materials can be found in the previous paper [6], [12]. Furthermore, the heating of 1 W was also considered in a warm enclosure to study the behaviour of moisture response.

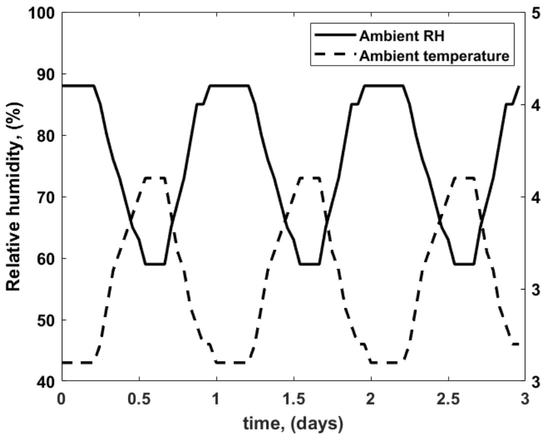
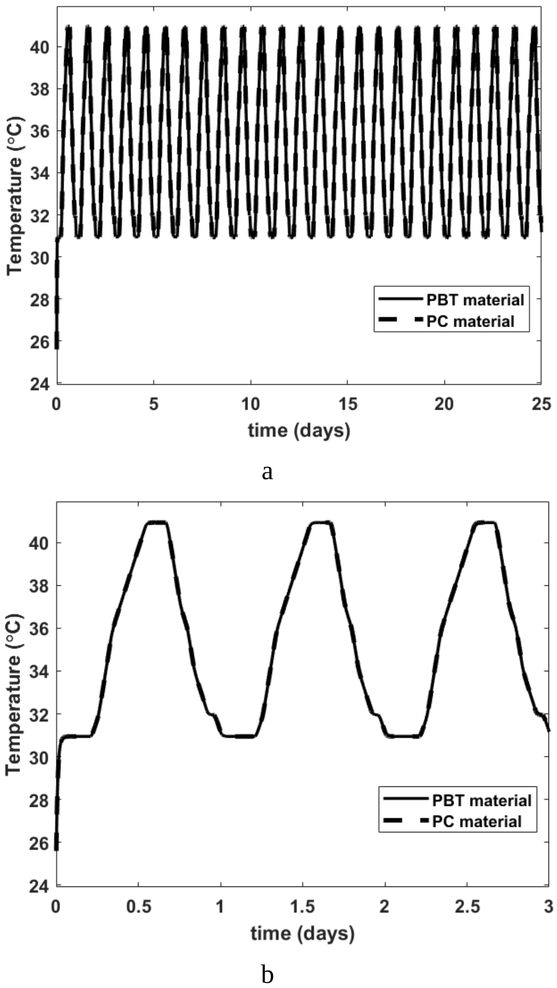


Fig. 5 Ambient temperature and relative humidity oscillations according to B3 STANAG climatic conditions



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b

Fig. 6 Temperature response in a warm enclosure when PC and PBT materials are considered: a) Full scale; b) zoomed scale of time

The heat transfer coefficient for inside and outside of investigated case is at 5 W/(m^{2}K). The convective mass transfer coefficient of 0.0041 m/s was calculated using Lewis relation [26].

The modelling was performed for 25 days and the first simulations were run with no heating in the warm enclosure. The temperature response depends on the ambient temperature and fluctuates in the same manner as the ambient conditions due to small thermal time constant (Fig. 6). Moreover, the temperature response is almost identical in both materials case due to similar thermal properties of both materials. It can also be seen that the temperature is almost the same as outside and it is not affected by the temperature of the cold enclosure. The temperature in a cold enclosure remains always at 4 °C and the heat flow remains constant between both enclosures and between cold enclosure and the ambient.

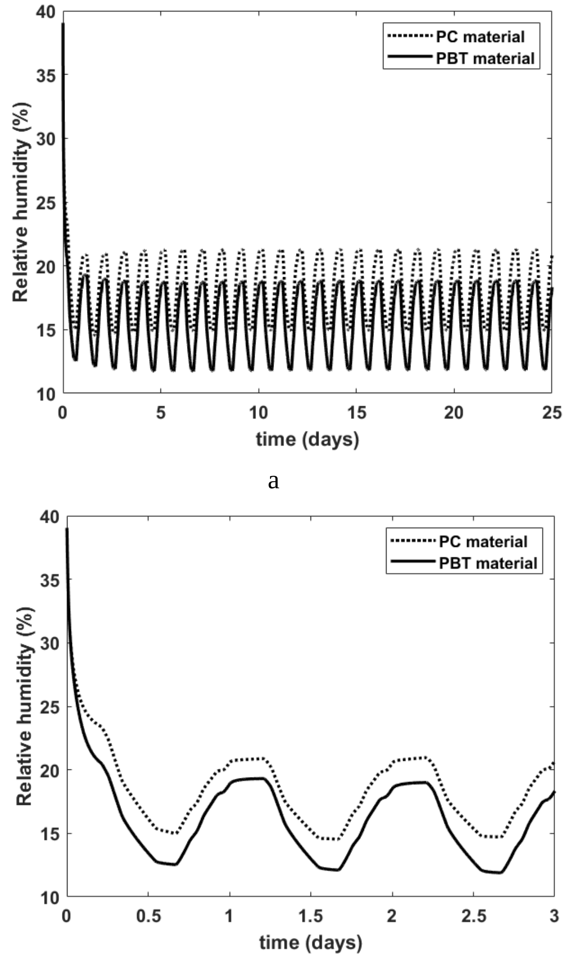

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Fig. 7 Relative humidity response in a warm enclosure when PC and PBT materials are considered: a) Full scale; b) zoomed scale of the relative humidity

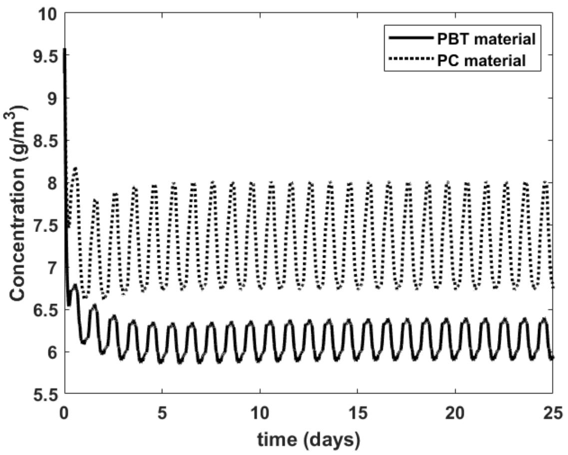
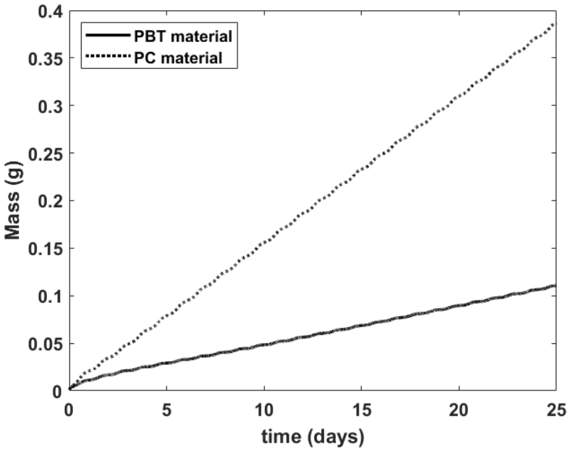


Fig. 8 Water vapour concentration response in a warm enclosure, two different materials are compared, namely, PC and PBT



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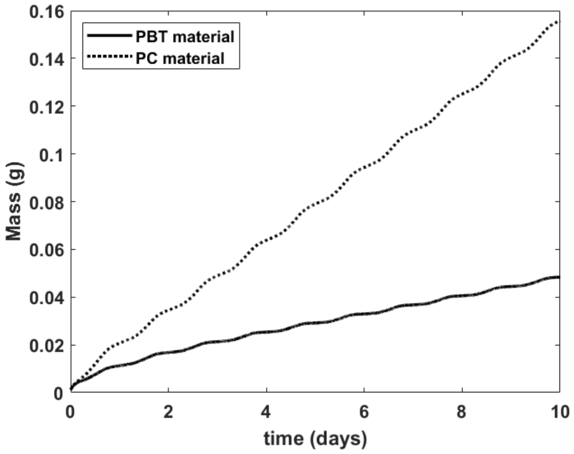

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Fig. 9 Mass of condensed water vapour in a cold enclosure, two different materials are compared, namely, PC and PBT: a) 25 days interval; b) 10 days interval

The following figures of relative humidity and concentration show how the moisture transport is affected by different material properties and the ambient conditions (Figs. 7 and 8). Initially, the relative humidity drops lower than 40 %, because there is a forced thermal gradient between two enclosures which causes the moisture transport towards the lower concentration region existing in the cold enclosure. The decrease of relative humidity is determined by the lower moisture flow from the ambient into a warm enclosure than from the warm into a cold enclosure through the tube. In case of PC material, the relative humidity is higher than using PBT material, because the moisture flow is higher through a PC material due to larger diffusivity. It can be seen that during the transient period until the steady state condition settles (from 0 to 5 days), the relative humidity grows when PC material is considered. When enclosure is made of PBT material, the RH reduces slowly until steady state condition settles. In a cold chamber, the relative humidity remains at 100% due to low temperature and indicates that condensation occurs constantly.

The concentration also drops more than the initial level in a warm enclosure. It also remains lower when the steady state condition settles (after 5 days) between the ambient and warm enclosure and between warm and cold enclosures. During this condition, the moisture flow from the ambient to a warm enclosure and from warm enclosure to a cold one become even. The concentration is also lower using PBT material. It is important to notice that PC and PBT gives a different concentration behaviour during the transient period from 0 to 5 days. This occurs due to different material's solubility and diffusion coefficients. In enclosure made of PC material, there is a moisture peak increase due to moisture release from walls of the warm enclosure which in turn causes a larger moisture flow from warm enclosure towards the cold enclosure. After moisture peak increase, RH follows a slow exponential increase of concentration. Contrary to PC material, the PBT material causes an exponential decrease of concentration due to its lower diffusion coefficient.

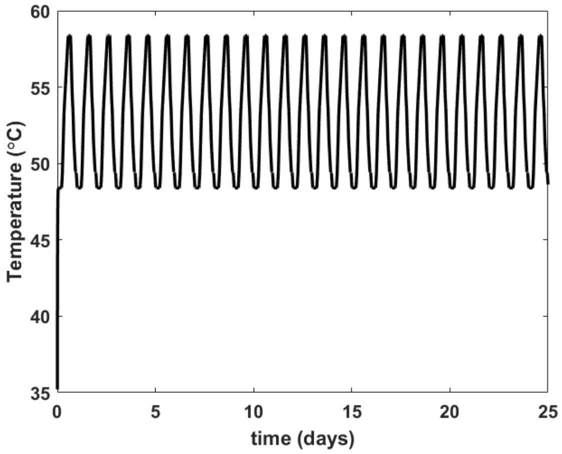
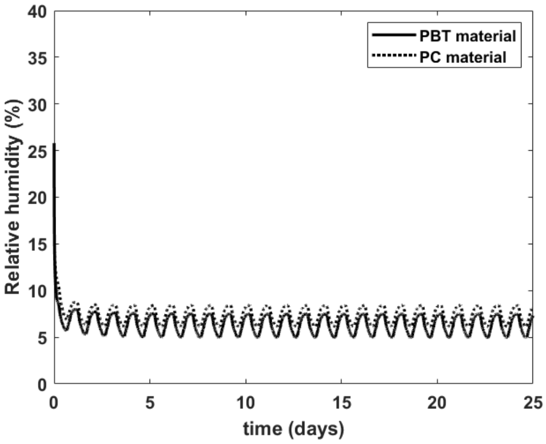


Fig. 10 Temperature response in a warm enclosure under 1 W of heating



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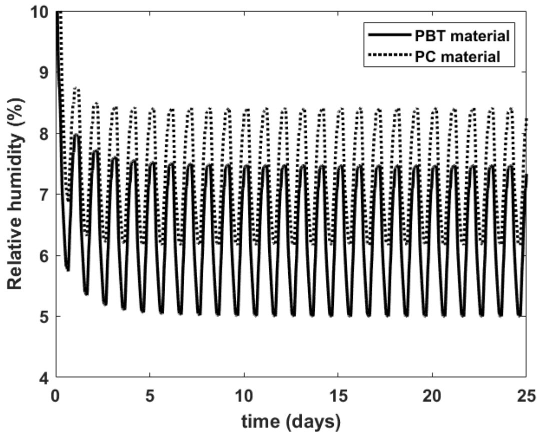

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Fig. 11 Relative humidity under 1 W of heating: a) Full scale; b) zoomed scale

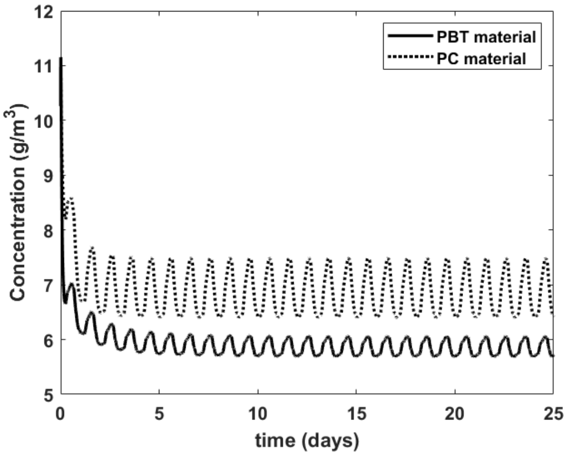
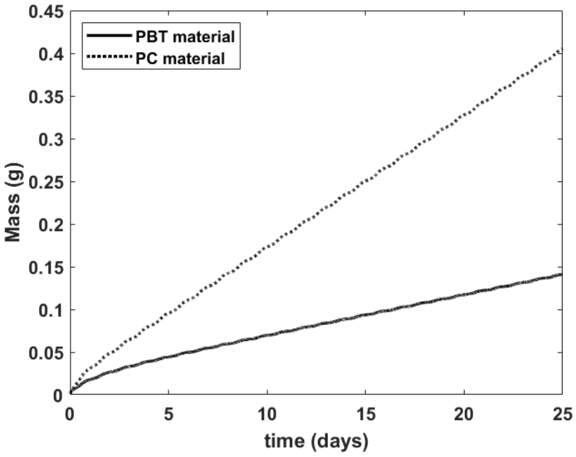


Fig. 12 Concentration of condensed water vapour in a warm enclosure when 1 W heating is applied

Concentration in a cold chamber is determined by the temperature and it reaches the saturation level equal to 6,35 g/m^3. Since the temperature is low in a cold enclosure, therefore the condensation occurs constantly. The thermal gradient between warm and cold enclosures creates a concentration gradient which causes a constant moisture transport from warm enclosure into the cold enclosure.



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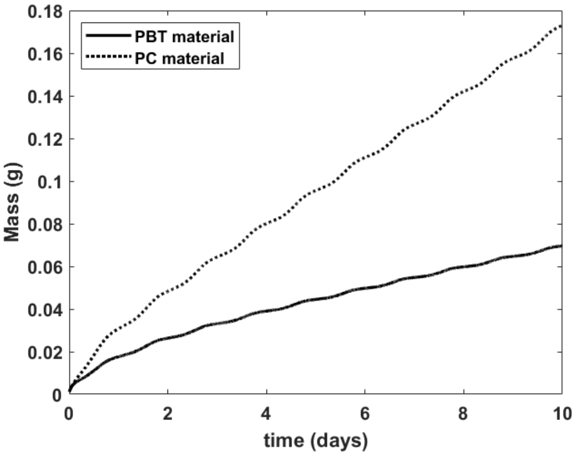

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Fig. 13 Mass of condensed water vapour in a cold enclosure when 1 W of heating is applied: a) 25 days interval; b) 10 days interval

The mass of condensed water vapour in a cold chamber is increasing constantly, however it fluctuates with regard to ambient conditions. The fluctuation is very small, because it depends on the warm enclosure water vapour concentration. In case of PC material, the concentration fluctuations are larger and therefore the mass fluctuation are a little larger than using PBT material. Comparing these materials, the PBT material results in smaller accumulation of the condensed water vapour due to its lower diffusion coefficient. Moreover, in the beginning of moisture transport process, the mass of condensed water vapour increases faster, because there is a larger moisture flow than during equilibrium.

When the heating is applied, the amplitude of RH and concentration response reduces, because of the increase in diffusivity and solubility which allows higher moisture flow through the wall between ambient and the warm chamber. Moreover, the temperature increases up to 58 °C, and it oscillates according to the ambient temperature. Concentration in both material cases behaves similarly and reduces exponentially until the steady state condition settles.

4. Conclusions

The study shows that PBT material is a better choice for having a lower relative humidity level in a warm enclosure and lower accumulated mass of condensed water vapour in a cold enclosure. Basically, the moisture flow is affected by the permeation (diffusivity and solubility) of moisture through the wall which is higher in PC than in PBT material. Moreover, diffusion and solubility coefficients are the most significant parameters in controlling the moisture transport.

The moisture transport from warm to the cold one is dependent on the ambient conditions. Higher humidity will determine higher moisture flow and vice versa. In both materials case, the relative humidity is lower than its initial value. During steady state condition, the moisture flow from ambient to a warm enclosure and from warm to a cold one is even. Both materials determined different behaviour of moisture in the transient period. Due to lower diffusion coefficient of PBT material, the concentration peak-to-peak amplitude was lower than in PC material case.

The temperature response was very fast because of small thermal time constant and followed the oscillations of ambient temperature.

The relative humidity and concentration were lower in case of internal enclosure heating. In fact, the peak-to-peak amplitude was also smaller. The accumulated mass of condensed water vapour was larger than without heating.

The developed in-house code provides a high flexibility of coupling different circuits for different physics under non-isothermal conditions. Moreover, the coupling of different dimensions, e.g., 0-D, 1-D, allows the optimization of a model and shortens the computational time.

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NUMERICAL MODELLING OF MOISTURE TRANSPORT BETWEEN TWO ENCLOSURES CONNECTED BY A TUBE

Summary

Electronic devices are typically protected using plastic or metallic enclosures. However, moisture from the surrounding environment can still enter the enclosure via gasket, plastic enclosure walls and cable feedthroughs. Further, the moisture existing inside an enclosure may condense on top of the PCBA or active electronic components, due to the faster temperature changes experienced by these devices as compared to the other regions within the enclosure, which can in turn lead to moisture-related failures. The local temperature inside an enclosure is dependent on the geometrical design of the enclosure as well as the heating behaviour of the electronic components.

The paper concerns the complex transient heat and mass transfer processes between two connected enclosures with one enclosure being warm, while another enclosure is cold. The objective of the paper is to develop an in-house code based on the RC approach for predicting and studying the temperature and moisture behaviour inside two connected enclosures. The developed RC model combines one-dimensional finite volume modelling techniques and lumped analysis methods for heat and mass transport. The modelling of temperature and moisture response is carried out under non-isothermal B3 STANAG ambient conditions. The different plastic materials of warm enclosure wall and the heating in the warm enclosure were studied.

Keywords: heat and moisture transport; absorption and desorption, temperature; RC approach; electronics enclosures; diffusion; solubility.

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