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Mathematical modelling of moisture transport into an electronic enclosure under non-isothermal conditions

Ž. Staliulionis [a,*], S. Mohanty [a], M. Jabbari [b], J.H. Hattel [a]

[a] Process Modelling Group, Department of Mechanical Engineering, Technical University of Denmark, Nils Koppels Allé, 2800 Kgs. Lyngby, Denmark
[b] Warwick Manufacturing Group (WMG), University of Warwick, Coventry CV4 7AL, UK

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A B S T R A C T

In contrast to high fidelity CFD codes which require higher computational effort/time, the well-known Resistor-Capacitor (RC) approach requires much lower calculation time, but has a lower resolution of the geometrical arrangement. Therefore, for enclosures without too complex geometry in their interior, it is more efficient to use the RC method for thermal management and design of electronic compartments. Thus, the objective of this paper is to build an in-house code based on the RC approach for simulating coupled heat and mass transport into a (closed) electronic enclosure. The developed code has the capability of combining lumped components and a 1D description. Heat and mass transport is based on a FVM discretization of the heat conduction equation and Fick's second law. Simulation results are compared with corresponding experimental findings and good agreement is found. Since, the paper concerns climatic cyclic conditions, a study is accomplished on investigating different material properties (thermal conductivity, diffusivity, solubility) for moisture control inside an enclosure. Further simulations were performed to study the response of temperature and moisture inside an enclosure exposed to the B2 STANAG climatic cyclic conditions. Moreover, the time for moisture build-up inside an enclosure under cyclic conditions is presented for different material properties.

1. Introduction

The use of electronic devices in climatically harsh environment leads to moisture-related failures, mainly corrosion due to water layer formation as well as leakage currents, short or open circuits caused by electrochemical metal migration [1–5]. These are few of the most important issues found in outdoor electronics applications, e.g. automotive industry and renewable energy sectors. Hence, knowledge of moisture transport into an electronic enclosure under environmental conditions becomes interesting for increasing the reliability of electronic components and devices.

The designs of enclosures for electronics systems are often based on years of experience, rather than scientific knowledge. The main bottleneck towards breaking this trend is to develop a set of more knowledge based modelling tools, which can further support the search for optimal designs and humidity control solutions. It is desirable to have fast modelling tools, since the computational time is of utmost importance in the whole electronics design, especially in the early product development stage, where all possible design configurations have to be considered. While CFD or FEM are widely used and extremely useful tools in moisture modelling, these methods are too time consuming due to computational effort [6–7]. Therefore it is highly desirable to have a method which has less spatial resolution and would be faster and sufficiently accurate to calculate the moisture response in the electronic systems.

The aim of this paper is to build an in-house code based on the RC approach for simulating coupled heat and mass transport into a closed electronic enclosure under non-isothermal conditions. Then, based on the developed code, the amount of moisture and heat transported via diffusion and heat conduction through a wall into an enclosure will be predicted.

The paper covers an in-house code development based on the RC approach in which a 1D description is combined with a lumped component for describing a polycarbonate (PC) enclosure. The 1D description of heat and mass transport in the wall is based on an FVM discretization of both heat conduction equation and Fick's second law while the lumped capacitance component is used to describe the interior enclosure volume. Simulation results were compared with corresponding experimental findings and good agreement was found. After validation of the code, a study is undertaken to investigate different material properties (thermal conductivity, diffusivity, solubility) for moisture control inside an enclosure. Then, next simulation was performed to assess the response of moisture and temperature inside a closed box to changes in B2 STANAG climatic cyclic conditions.

* Corresponding author.
E-mail address: zygsta@mek.dtu.dk (Ž. Staliulionis).

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2. Moisture and temperature modelling via RC approach

This section outlines the development of an in-house code based on the RC approach for analyzing the response of moisture and temperature under non-isothermal conditions. Here, the RC approach is applied to solve heat and moisture transport based on heat conduction equation and Fick's second law [8–9].

The code is only developed to study a closed electronics box. In reality, the moisture and temperature inside a closed box of air reaches equilibrium relatively fast, therefore the convection is not considered in the code. Moreover, the following is assumed:

- The temperature is considered to be uniform on the outer and inner surface of box and in the air. The applicability of this assumption is dependent on the electronics box being modelled. In large electronics enclosures, the assumption of uniform temperature might not be valid if the temperature difference between any two locations in the box is sufficiently large. As a consequence, the RC circuit would be changed with further discretization into smaller lumped sub-components along surface (where the uniform temperature assumption would be acceptable). Then such RC circuits in Fig. 2a would be connected in parallel having separate uniform temperature source and charging the same interior lumped capacity component $C_{air,th}$.
- The convection inside the cavity and in the ambient atmosphere is assumed to be sufficient to maintain spatially constant densities of water vapour in each of the two regions.

The next Subsection 2.1 relates to the development of the RC model in more detail under the considered assumptions and applied equations.

2.1. Thermal-moisture RC circuit

The closed electronics enclosure in Fig. 1 is used to model the response of moisture and temperature.

Two separate RC circuits are implemented in the code. First, the moisture response inside the enclosure is simulated by using an equivalent circuit consisting of multiple resistors and capacitors (RC hygro-circuit) where the concentration in the air or in the wall is represented as voltage (Fig. 2b) [7]. Second, the temperature response is simulated using the same or a different configuration RC circuit (RC thermo-circuit). The temperature is also represented as the voltage (Fig. 2a). The thermal and moisture resistances of discretized elements are expressed below:

$$R_{\text{element,th}} = d_e/kA \quad \text{and} \quad R_{\text{element,m}} = d_e/DA \tag{1}$$

The capacity for the moisture is equal to the actual volume of material (V_{wall} or V_{air} in Fig. 1) and the thermal capacity is given by the equation below:

$$C_{\text{element,m}} = V \quad \text{and} \quad C_{\text{element,th}} = \rho c_p d_e A \tag{2}$$

where D – diffusion coefficient for a given temperature in m^2/s, A –

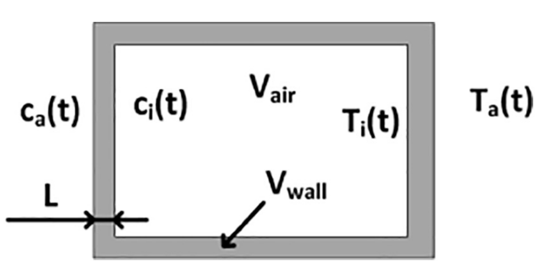

Fig. 1. Illustration of the investigated box.

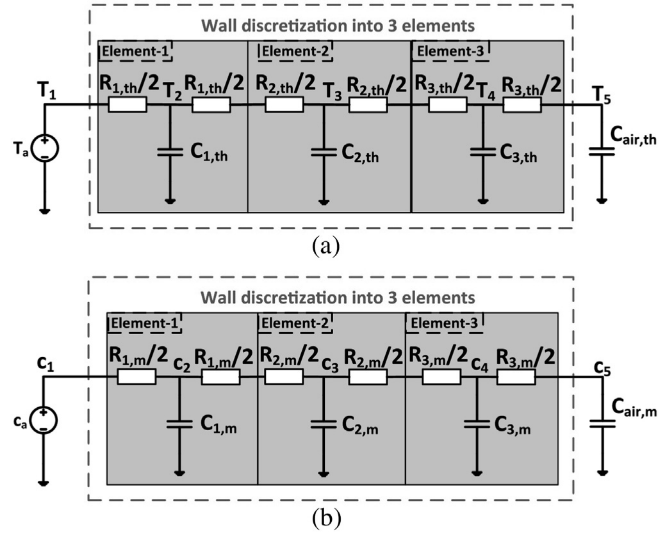

Fig. 2. RC circuit for modelling (a) temperature and (b) moisture.

surface area of element perpendicular to the flow of heat or moisture in m^2, d_e – length of element of discretized domain in m, ρ – density in kg/m^3, k – thermal conductivity in $W/(m\cdot K)$, c_p – specific heat capacity in $J/(kg\cdot K)$, V – volume in m^3, m – moisture, th – thermal.

The two RC circuits are coupled where the thermal field and concentration distribution are coupled via the diffusivity and solubility equations shown below [7–8]:

$$D(T) = D_0 e^{\left(\frac{-E_D}{RT}\right)} \tag{3}$$

$$S(T) = S_0 e^{\left(\frac{E_S}{RT}\right)} \tag{4}$$

where D_0 – pre-exponential factor/coefficient, m^2/s, R – universal gas constant, $J/(mol\cdot K)$, E_D – activation energy for diffusivity, J/mol, T – temperature, K, S_0 – pre-exponential factor/coefficient, $kg/(m^3\cdot Pa)$, $J/(mol\cdot K)$, E_S – activation energy for solubility, J/mol. Furthermore, the material's thermal conductivity is not dependent on the concentration in this study.

In this study, the wall of the box is discretized into three elements and the box interior is considered to be a lumped component (Fig. 2). The same configuration is used for both RC thermal and hygro-circuits. The coupled thermo-hygro-circuit is solved implicitly (Backward Euler method) [9] in order to use an unconditionally stable scheme allowing for higher time increments. The boundary conditions are implemented as voltage source in the thermo-hygro-circuit. Moreover, Matlab software was used to solve thermo-hygro-RC circuit.

2.2. Discontinuity at the environment and material interface

The concentration of water vapour is discontinuous at the environment-material or material-material interfaces (Fig. 3) [7,10].

Basically, the water vapour concentration represented by voltage in the RC circuit should be equal in all capacitors or nodes when equilibrium is reached in the diffusion process. Since, different materials have different solubility levels (Fig. 3), these materials have to be normalized with respect to a reference material in order to avoid discontinuity and to enable usage of RC circuit for moisture modelling. Therefore, an actual volume of each material is represented by the equivalent reference material volume which stores the same amount of water vapour as each actual material. Such modification is broadly discussed in the paper [7]. Usually, air is chosen as a reference material to normalize the RC hygro-circuit.

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