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A 3D numerical study of humidity evolution and condensation risk on a printed circuit board (PCB) exposed to harsh ambient conditions

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A R T I C L E I N F O

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A B S T R A C T

In many applications, electronics enclosures are exposed to harsh environmental conditions. For a reliable design, it is crucially important to understand the effects of such conditions on the local climate inside the enclosures. In this study, the relative humidity (RH) and temperature inside an electronic enclosure exposed to harsh ambient conditions (relative humidity of 100% and cyclic temperature changes from 10 to 50 (°C)) are studied by developing a full 3D finite element based CFD model. The RH evolution is studied in three stages: first, in an empty enclosure, then in an enclosure with a PCB, heatsink and a heater, and finally in the case of an internal cyclic heat load. In all three parts, the effect of the opening size of the enclosure is also studied. The numerical simulation results are compared with corresponding experimental results from the literature, and a good agreement is found.

The presence of components inside the enclosure damps the response of the internal climate to the ambient changes and this is especially the case for the aluminum heatsink. In case of exposure to RH of 100%, controlling the moisture concentration appears to be more effective than controlling temperature with the aim of reducing the condensation risk on the PCB.

1. Introduction

Thermal performance is identified as one of the primary goals in electronics system design. In fact, the prediction of thermal performance of electronic equipment is a necessity in order to reduce the time to bring products to the market [1–3]. Beside thermal management, humidity management and condensation risk are major concerns. Exposure to high relative humidity (RH) leads to condensation of water on the printed circuit boards (PCBs). The concentration of water molecules rises as the RH increases. The thickness of the molecular layers of water eventually permits ionic conduction which can lead to changes in electrical resistance and even short circuits. This phenomenon accelerates the rate of corrosion. Hence, in order to protect electronic devices from the effects of water vapor, it is essential that the RH inside the enclosure does not reach a level that threatens the electronics functionality within the required lifetime [4–8]. Depending on the electronics design and its cleanliness, the critical range of RH for corrosion failure varies from 60% to 90% [3,9,10].

Generally, moisture can get into electronics enclosures in two ways: firstly, the moisture is sealed into the package during manufacturing. This quantity of water is fixed at the assembly time and the moisture may reside in the trapped air, be adsorbed to free surfaces or dissolved in component materials. It should be noted that even for hermetically sealed enclosures, this moisture must be considered. The second source of moisture ingress is leakage or permeation into the package from the external environment. The magnitude of this contribution changes with storage time and depends on the details of the seal design as well as the storage conditions [9]. Considering the fact that, moisture related failures are related to the RH rather than the absolute humidity, thermal and humidity management are strongly interconnected [10]. By definition, relative humidity is the ratio of the absolute humidity to the maximum possible (saturated) absolute humidity at a specific temperature.

Thus, *RH* can be maintained below the threshold value either by maximizing the saturation limit (thermal control) or by minimizing the absolute humidity (moisture control) [11].

Belov et al. [8] employed a heater on the critical places for condensation, in order to keep the temperature of these critical places for condensation higher than the dewpoint (maximizing saturation limit). In their work, beside the experiments, the simplifying Boussinesq approximation was used to develop a 3D computational fluid dynamics (CFD) model for a parametric study. In another study, Hygum and

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Nomenclature

C_p	specific heat of the fluid at constant pressure (J/kg·K)
c	concentration of the species (mole/m^3)
D	moisture diffusion coefficient (m/s)
F	volume force vector (N)
g	acceleration due to gravity (m/s^2)
I	unit tensor
p	pressure (pa)
T	temperature (K)
t	time (s)
u	velocity vector (m/s)

Greek symbols

μ	dynamic viscosity (Pa·s)
ρ	mass density (kg/m^3)

Subscripts

x, y, z	direction coordinates

Popok [12] also utilized the Boussinesq approximation to numerically study the humidity evolution on the electronics inside an enclosure with an opening using a 2D model (minimizing the absolute humidity). Bayerer et al. [13], Tencer and Moss [11,14] and Dahan et al. [15] applied quasi-steady-state (QSS) models to study moisture transfer into electronics enclosures. These models apply resistance-capacitor circuits based on the hygro/thermal -electrical analogy [11,13–15]. Despite the significance of the effect of humidity management on the lifetime of the electronics, there are only a few papers which have focused on this issue.

Numerous parameters affect the local climate inside electronic enclosures, such as material properties, dimensions of the enclosure and the electronics, components and their configurations and finally environmental conditions. Ambient condition changes are significantly affecting the local climate inside electronic enclosures. In applications such as military, industrial, commercial or consumer electronics, certain equipment may contain devices highly sensitive to environmental conditions. Understanding the effects of these conditions on the local climate inside the electronic enclosures and applying this knowledge during the design improves the reliability of the equipment and consequently reduces failures and maintenance costs [6,16,17]. In the above mentioned studies, simplified models have been used to describe the heat and mass transfer. However, nowadays, the power of computers allow us to handle larger models.

In order to precisely predict the local climate inside electronics enclosures, one has to perform coupled momentum, heat and mass transfer analysis on the system composed of several components of various sizes (such as PCBAs, heatsinks …) in a tight space. The method of choice for making such predictions is mostly CFD [14,18,19]. Application of CFD analysis for the thermal design of electronics systems has the potential to provide accurate solutions and to assess them in different cases [19].

The aim of the present study is to investigate the effect of ambient conditions on the RH evolution on a PCB placed in an electronics enclosure. To achieve this purpose, a full 3D CFD model is developed for a typical aluminum enclosure with a PCB, heatsink and a heater inside, with an opening.

In order to look into the effect of both maximizing the saturation limit and minimizing the absolute humidity, four different cases are defined. In the first two cases, an empty enclosure is exposed to cyclic ambient temperature and high RH with two different opening sizes. In the other two cases, the PCB, heatsink and heater are located inside the enclosure exposed to the same ambient conditions with two different opening sizes, as before. The effect of an internal cyclic heat load to the PCB is also studied.

The commercial software package COMSOL Multiphysics™ version 5.1 is used for running all the CFD simulations. The simulation results for temperature are compared with experimental data from a similar work in the literature.

2. Theory and methods

2.1. Geometries and governing equations

Fig. 1 presents the studied symmetry geometries in case of a) an empty enclosure and b) an enclosure with the components (PCB, heatsink and heater) inside. Table 1 shows the dimensions of each of these components. These parameters are typical of outdoors electronics enclosures [16].

In this work, to estimate the velocity profile caused by volumetric forces, the energy equation is fully coupled with the momentum and continuity equations. Fig. 2 demonstrates the way that these equations are coupled. The continuity equation or equation for the overall mass balance is:

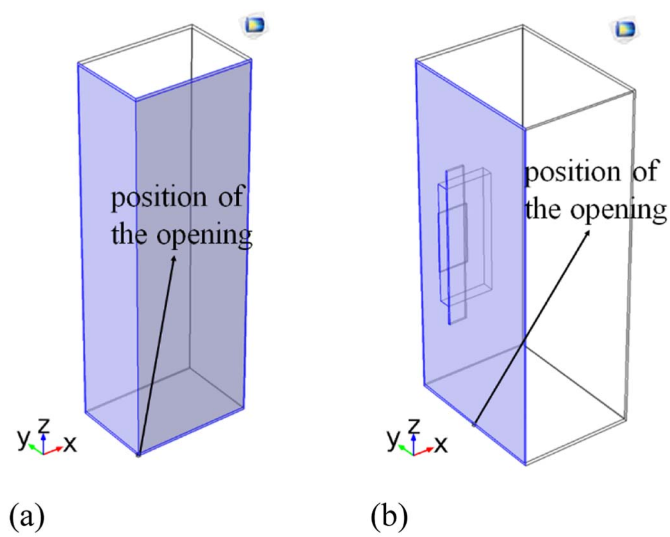

Fig. 1. Illustration of the investigated geometries; (a) empty enclosure, (b) enclosure with components inside (symmetry faces are shown in blue). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
The dimensions of the geometries.

Item	Dimensions (mm)	Material
Enclosure	Inner: 188 × 128 × 276 Outer: 190 × 130 × 280	Aluminum
Heater	50 × 1 × 50	Silicon
Heatsink	80 × 10 × 100	Aluminum
PCB	30 × 1.6 × 130	Compact FR-4 and copper layers