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Numerical Simulation of Moisture Condensation Risk in Electronic Board Enclosures: Parametric Study of Ventilation Design and Material Effects

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ABSTRACT

The reliability of electronic devices can be significantly compromised by moisture condensation within enclosures, leading to corrosion, electrical faults, and pollution accumulation. To address this, a numerical simulation study investigated the impact of ventilation hole dimensions and placement, enclosure material (aluminum, polystyrene, and polyvinyl chloride), and enclosure size under realistic 24-hour weather conditions in humid (Nowshahr) and dry (Tabriz) regions of Iran. Analyzing 15 distinct models through 24-hour transient simulations, the research found that in humid winter conditions, enclosures experienced over 14 hours daily with relative humidity exceeding 95%. Key results indicate that placing ventilation at the top minimizes condensation, and while more holes don't guarantee improvement, their location is critical. Smaller ventilation holes increase condensation, while larger ones are more effective. Notably, polymeric enclosures reduced condensation risk by 19.6-20.6% compared to aluminum in humid climates, whereas increasing enclosure size from 50mm to 100mm only yielded a 2-3% reduction. These findings provide valuable guidance for designing electronic enclosures that effectively mitigate moisture and enhance device longevity.

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Introduction

The environment and its various characteristics can significantly affect electronic boards. One of the most common environmental effects that has a noticeable effect on the performance of electronic boards is relative humidity. Moisture can lead to corrosion and rusting of the metal components of the electronic board, disruption of electrical circuits, reduction of useful life, and accumulation of pollution on the electronic board, each of which in turn can disrupt the performance of electrical components and lead to the loss of effective electrical connections [1-3]. In addition, moisture can change the insulation properties of the materials used in the electronic board, which can reduce the electrical security of the device and increase the risk of accidents such as electrocution [4-5]. The meaning of humidity is water in the gas phase that is dispersed in the air as vapor. Humidity is known as a measure of the amount of water vapor in a gas (usually air) and is generally defined as absolute humidity and relative humidity. Absolute humidity is the amount of mass of water vapor in kilograms or grams that is present in a unit volume of air, while relative humidity specifies the current ratio of water content to the maximum water content. Condensation refers to the change of vapor state to liquid water and occurs when the relative humidity reaches 100%. It can be achieved by increasing the concentration of moisture in the air or decreasing the temperature to the saturation point. The state of condensation appears in the form of a water drop or water film, depending on the type of surface [6]. The majority of scholarly investigation [7-18] has concentrated on the materials used in the manufacturing of electronic components. In contrast, a more circumscribed subset of research has been dedicated to elucidating the influence of relative humidity on the operational characteristics of electronic boards, with selected instances presented subsequently. In his research, Khoshnav studied the effect of humidity and pollution on the performance of electronic equipment. He showed that the penetration of water molecules and pollutant ions causes serious disruption in the performance of electronic equipment and increases the energy required for signal transmission [19]. In another study, Grandi gave suggestions for optimal temperature and humidity according to environmental conditions [20]. Also, in research, Jakonen et al. studied the thermal performance and the effect of temperature on electronic components (lighting systems). The data provided by them provides information about the changes in the cooling parameter as well as about the average and worst environmental conditions at night, which are experienced by outdoor LED lamps. This information can be considered in lamp cooling design as well as in research on thermal management, reliability, and optical performance of outdoor LED lighting systems [21]. Circuit analysis to predict moisture-related failures in electronics was done by Jashi et al. They provided methods and recommendations to improve the performance of electrical circuits [22]. Conseil-Gudla et al. [23] conducted an experimental investigation into the water absorption and regeneration performance of various desiccants. Their analysis and test results demonstrated that a desiccant system can continuously maintain lower humidity levels within electronic enclosures during cyclic exposure, provided it can be regenerated using the device's self-generated heat. The review by Bahrua et al. [24] synthesizes current research on the simulation design of thermal models for electronic devices. The increasing compactness and power of electronic devices underscore the crucial role of effective thermal management in ensuring their reliability, performance, and longevity. Simulation is vital in the design and optimization of thermal solutions, enabling engineers to predict and analyze heat generation and dissipation within these complex systems. Acknowledging a research gap in the existing literature, this research numerically simulated the risk of moisture condensation on electronic boards using COMSOL software. It analyzes the impact of ventilation hole dimensions and location, enclosure material, and overall enclosure dimensions on this condensation phenomenon. Transient simulations, conducted over a 24-hour cycle, were employed to investigate 15 distinct models. These models systematically varied in their geometric configurations and/or material compositions and were analyzed under diverse weather conditions.

Description of the problem

Environmental conditions and humidity play a vital role in the reliability of electronic boards, significantly impacting their performance through corrosion, electrical circuit disruptions, and the accumulation of pollutants on wet surfaces. Therefore, this research focuses on the risk of moisture condensation on electronic boards across diverse weather patterns. A comparative case study of Nowshahr and Tabriz cities was performed, utilizing simulations of 15 distinct models under non-steady conditions. Figure 1 illustrates the simulated geometry, and Table 1 presents additional specifications. The thermophysical properties of the materials and the weather data (temperature and humidity charts) for the selected cities are detailed in Table 2 and Figures 2 and 3.

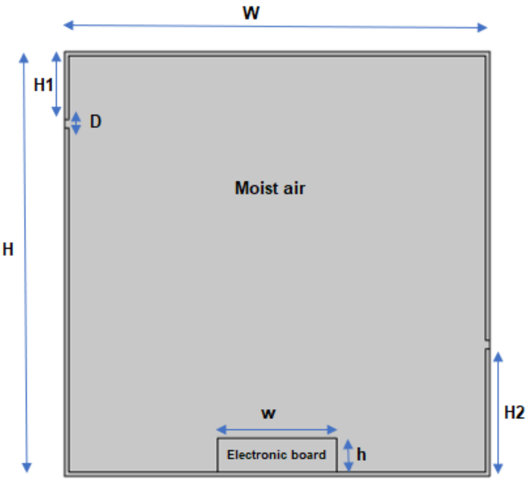


Figure 1. Schematic of the studied geometry.

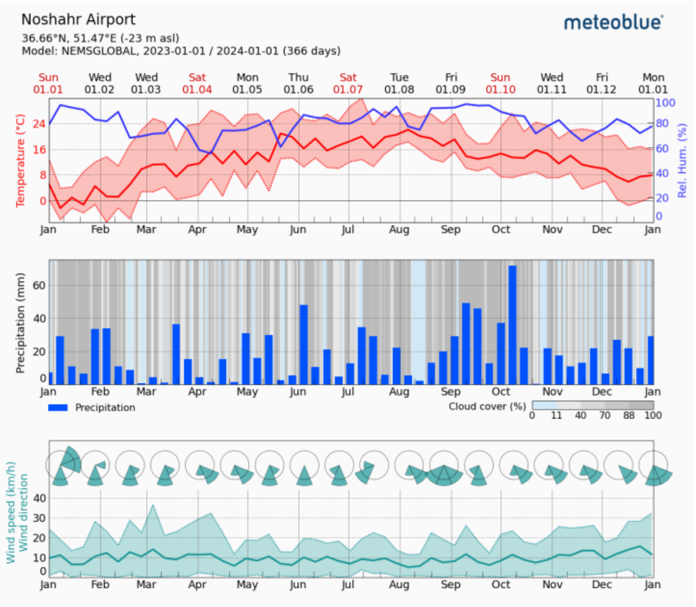


Figure 2. Climate characteristics of Nowshahr city, Iran [25].

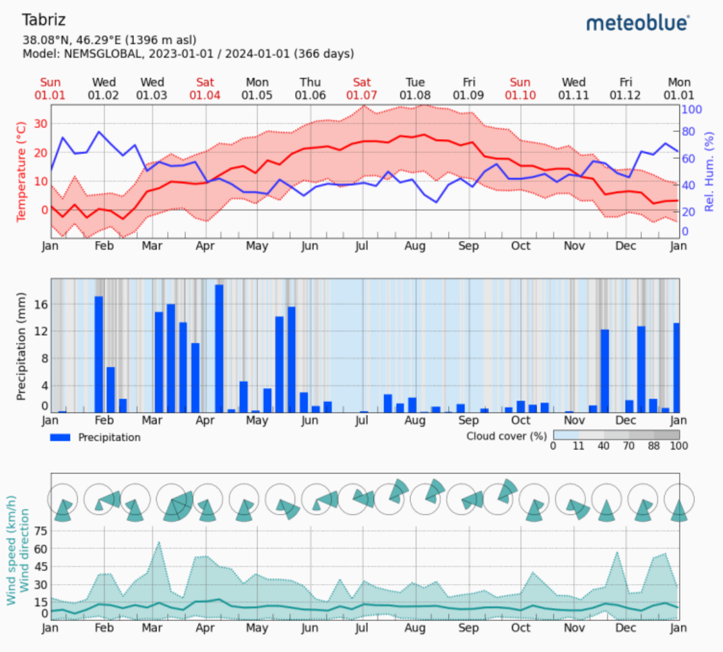


Figure 3. Climate characteristics of Tabriz city, Iran [26].

Table 1. Geometric specifications of the studied models

Geometric specifications	Size	Geometric specifications	Size
H	50	w	14
W	50	H1	9
D	1-8	H2	15
h	4		

Table 2. Thermophysical characteristics of materials

Material	Density(m^3/kg)	Heat Capacity J/(kg·K)	Thermal Conductivity W/(m·K)	Water Vapor Permeability (kg/(m·s·Pa))	Water Contact Angle (°)
Aluminum	2700	900	238	10^{-18}	80
Silica glass	2203	703	1.38	10^{-15}	30
Polystyrene	1050	1250	0.14	10^{-13}	100
polyvinyl chloride (PVC)	1380	1000	0.16	10^{-14}	90

Boundary conditions

Given the prevalence of natural convection conditions within the studied enclosures, a convection coefficient (h) of 10 W/m²K is adopted for air. This value aligns with typical ranges reported in the literature [27] for natural convection scenarios. Also due to the compact size of the electronic board examined in this study, a power dissipation of 1 W has been adopted as a realistic value. The temperature and humidity of the external environment and the material of the enclosure vary according to the weather conditions and the type of selected material. Also, the boundary condition at the entrance of ventilation holes is considered to be an open boundary condition.

Solution method and governing equations

This study employs a two-dimensional numerical model developed within COMSOL 6.1 software to simulate heat transfer and fluid flow within the enclosure, encompassing the electronic board with ventilation holes. The model accounts for the transport of water vapor (humidity) via both natural convection and diffusion, which are significant due to air movement and concentration gradients. Transient simulations were conducted by solving the momentum and energy equations based on the underlying physics of the problem. For the continuous air phase, incompressible and laminar fluid flow was assumed due to the low flow velocities, and the Navier-Stokes equations were utilized [28]:

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho\mathbf{u}) = 0 \tag{1}$$

$$\rho\frac{\partial \mathbf{u}}{\partial t} + \rho(\boldsymbol{u}.\nabla)\mathbf{u} = \nabla.[-p\mathbf{I} + \mathbf{K}] + \mathbf{F} + \rho\mathbf{g} \tag{2}$$

Where **I** is the unit matrix and **K** is:

$$\mathbf{k} = \mu(\nabla\mathbf{u} + (\nabla\mathbf{u})^T) - \frac{2}{3}\mu(\nabla.\mathbf{u})\mathbf{I} \tag{3}$$

The heat transfer within the moist air domain was simulated using the "Heat Transfer in Moist Air Interface" in COMSOL Multiphysics 6.1. This interface solves a modified energy equation that incorporates the effects of humidity on heat transfer [29]:

$$\rho c_p\frac{\partial T}{\partial t} + \rho c_p\mathbf{u}.\nabla T + \nabla.\mathbf{q} = \mathrm{Q} + q_0 + Q_P + \mathrm{Q}_{\mathrm{vd}} + Q_H \tag{4}$$

Here, the terms q, q_0, Q_v, and Q_P are defined as:

$$\mathbf{q} = -k\nabla T \tag{5}$$

$$q_0 = h(T_{ext} - T) \tag{6}$$

$$\mathrm{Q}_{\mathrm{vd}} = \tau:\nabla\mathbf{u} \tag{7}$$

$$Q_p = \alpha_p T(\frac{\partial P}{\partial t} + \mathbf{u}.\nabla p) \tag{8}$$

where Q represents the heat generated by internal heat sources, and the remaining terms in Equation 4 account for heat conduction, convection, and the influence of viscous dissipation and pressure work. Crucially, the model incorporates the Q_H term, representing the diffusive flux of thermal enthalpy due to water vapor concentration gradients within the moist air mixture. As detailed in Ref. [30], this term is defined as:

$$Q_H = -\left(C_{P,v} - C_{P,a}\right)\mathbf{g}_w.\nabla T \tag{9}$$

In this equation, $C_{P,v}$ and $C_{p,a}$ are the specific heat capacities at constant pressure for water vapor and air, respectively. The term $\mathbf{g}_w$ represents the vapor flux due to diffusion, calculated according to the following equations:

$$\mathbf{g}_w = -\rho_g D \nabla_{\omega_V} \tag{10}$$

$$\rho_g \frac{\partial \omega_V}{\partial t} + \rho_g \mathbf{u}.\nabla_{\omega_V} + \nabla.\mathbf{g}_w = \mathrm{G} \tag{11}$$

$$\omega_V = \frac{M_V C_V}{\rho_g} \tag{12}$$

$$C_V = \emptyset_w C_{sat} \tag{13}$$

where M_v is the molar mass of water vapor, ϕ_W is the relative humidity, C_{sat} is a constant related to saturated vapor concentration, D is the vapor diffusion coefficient, and G represents any moisture sources.

Physically, the Q_H term arises because the diffusion of water vapor carries its associated thermal enthalpy. When a concentration gradient exists, the diffusion of vapor (or air) results in a net heat transfer if the specific heat capacities of the two components differ. This mechanism becomes significant in scenarios involving varying humidity levels. Using the governing equations 1 to 13, the simulation of the studied model was performed to investigate the effect of various parameters, including the location and dimensions of the ventilation holes, as well as the material and dimensions of the enclosure, on heat transfer and fluid flow.

Result and discussion

Validation

The accuracy of the present numerical model in predicting condensation within electronic enclosures was assessed by comparing its results to the experimental study conducted by Staliulionis et al. [31]. Their research provides detailed measurements of transient temperature and relative humidity within an aluminum enclosure subjected to controlled oscillating ambient temperatures, directly capturing the complex interplay of heat and mass transfer leading to condensation. The simulated temperature and relative humidity profiles on the inner wall surface of the enclosure showed good agreement with the experimental data (Figures 4,5), indicating the model's capability to capture the key physical phenomena. Moreover, a calculated Root Mean Squared Error (RMSE) of approximately 2% supports the conclusion of acceptable simulation performance.

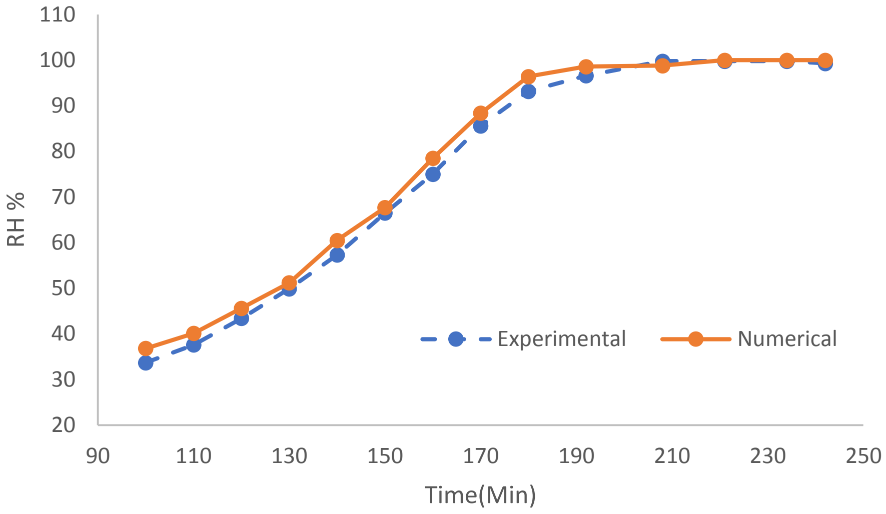


Figure 4. **Relative humidity over time: Comparison of the current model's simulation and experimental results from Staliulionis et al. [31].**

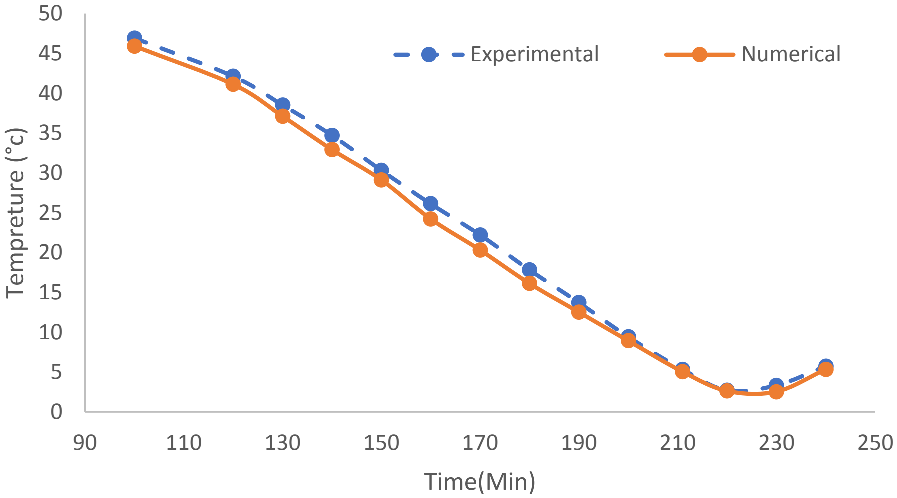


Figure 5. **Tempreture over time: Comparison of the current model's simulation and experimental results from Staliulionis et al. [31].**

Mesh Independency

In order to check the independence of the presented numerical model from the computational grid and to ensure insignificant changes of the evaluated quantity by refining the computational grid, the studied problem has been simulated in three different types of mesh (Table 3). Figure 6 shows the relative humidity as a function of time in these cases. As it is observed, the results in the cases where the number of mesh elements is 7330 or 5594 are nearly the same, while the difference is large for the case where the number of mesh elements is 2531. Therefore, to obtain more accuracy in results with the minimum computational costs, a finer grid resolution (case 2) is considered.

Table 3. Geometric specifications of the studied models

	Number of elements	Average element quality
Normal mesh	2531	0.768
Finer mesh	5594	0.812
Extra fin mesh	7330	0.818

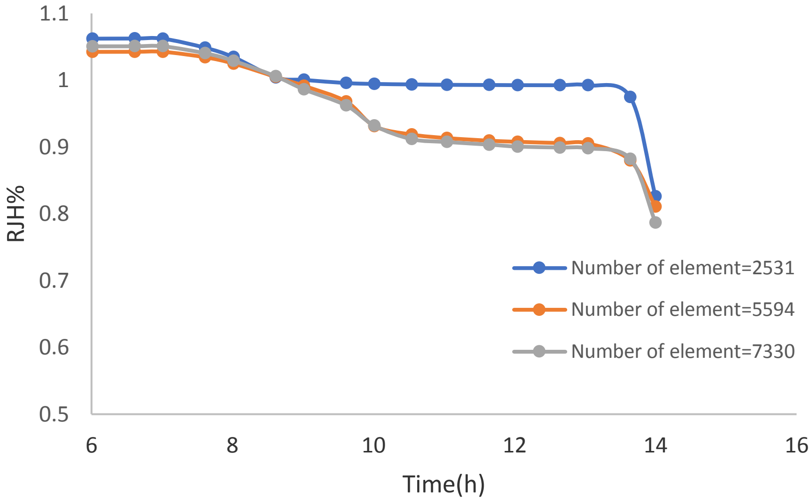


Figure 6. Relative humidity changes diagram of the simulated model for different number of nodes in order to check the independence of the network.

Simulation of Air Humidity Condensation Risk on Electronic Boards

Considering the adverse effects of humidity on the performance of electronic boards, in this research, the risk of condensation of air humidity on the electronic board has been numerically simulated using COMSOL software. In order to investigate the effect of weather on the studied problem, simulations have been carried out for the first day of January in the two cities of Nowshahr and Tabriz with wet and dry weather, respectively. The studied geometry and thermophysical characteristics of the materials in both models simulated in this section are the same, according to Figure 1 and Tables 1 and 2. Figure 7 shows the changes of relative humidity during the first day of January inside the electronic enclosure for Nowshahr city. As it can be seen, due to the high humidity of Nowshahr city and as a result of moisture infiltration through holes into the electronic enclosure, the relative humidity of the air inside the enclosure is around 90% only during the hours of 14:00 to 22:00 and the humidity is 100% during the rest of the day. In other words, in a period of about 14 hours, moisture condensation occurs on the internal surfaces of the enclosure and the electronic board, which is very undesirable, and there is a risk of damage to the electronic board. It should be noted that in the simulation, the electronic board is considered as a heat source.

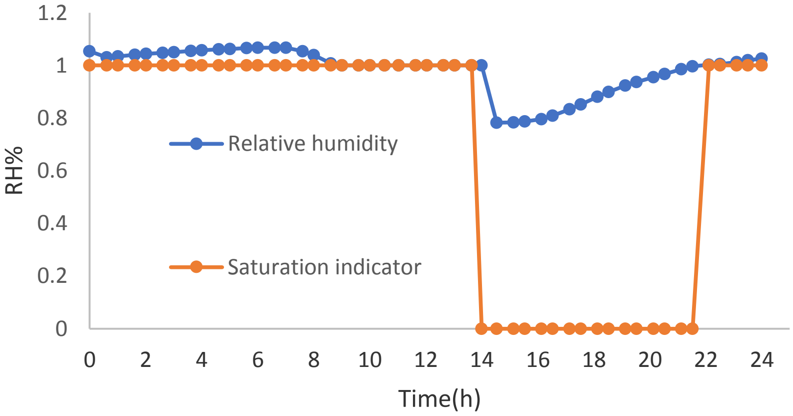


Figure 7. **Relative humidity changes over time in the studied electronic enclosure for Nowshahr city.**

The relative humidity changes during the first day of January inside the electronic enclosure for the city of Tabriz are shown in Figure 8. As can be seen, the highest relative humidity is around 7:00 am and is 97%; in other words, there is no risk of moisture condensation in the compartment and on the electronic board. Therefore, it can be concluded that there is no risk of moisture condensation for cities with climate conditions similar to Tabriz or drier.

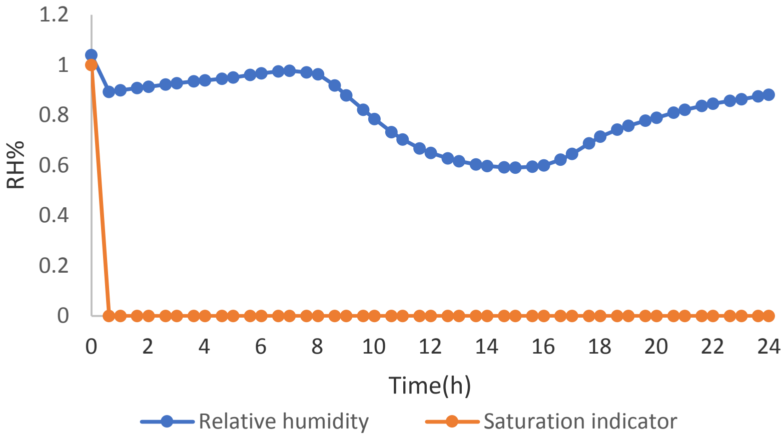


Figure 8. **Relative humidity changes over time in the studied electronic enclosure for Tabriz city.**

The effect of the location of the holes

One of the effective parameters in the amount of condensation of air humidity on the electronic board is the placement and location of the holes in the enclosure, so in this research, by changing the location and number of ventilation holes and placing them on the top, bottom, and right side, in two cases, 2 holes and 3 holes, the amount of moisture condensation on the surfaces of the electronic enclosure is compared with the base case. Other parameters are kept constant for comparison.

A) The case of two ventilation holes

The modeling done in this section includes two holes; one hole is placed on the left side of the enclosure, and the second hole is placed in three different positions, top, bottom, and right. Figure 9 compares the amount of moisture condensed over time on the interior of the electronic enclosure for three configurations with two ventilation holes. The data reveals that placing the second hole at the top minimizes condensation, whereas locating it at the bottom or right (around 8:30 AM) significantly increases condensation to approximately 116.2 mg/cm² and 91.6 mg/cm², respectively. In other words, the highest moisture condensation is related to the position of the hole in the lower position, and the lowest condensation is related to the placement of the hole in the upper position of the enclosure.

The reason for this phenomenon is that the flow of moist and cold ambient air enters the enclosure through the holes, and inside the enclosure it is affected by the air heated by the electronic board and circulates due to a difference in density and natural convection. Now, when the second hole is placed on the bottom and right side of the electronic board, due to the fact that the first hole is located on the left and top side, the most air circulation, as a result, the most mixing of warm and cold air and diffusion of moisture occur. Therefore, moisture condensation reaches the highest value compared to the other two modes.

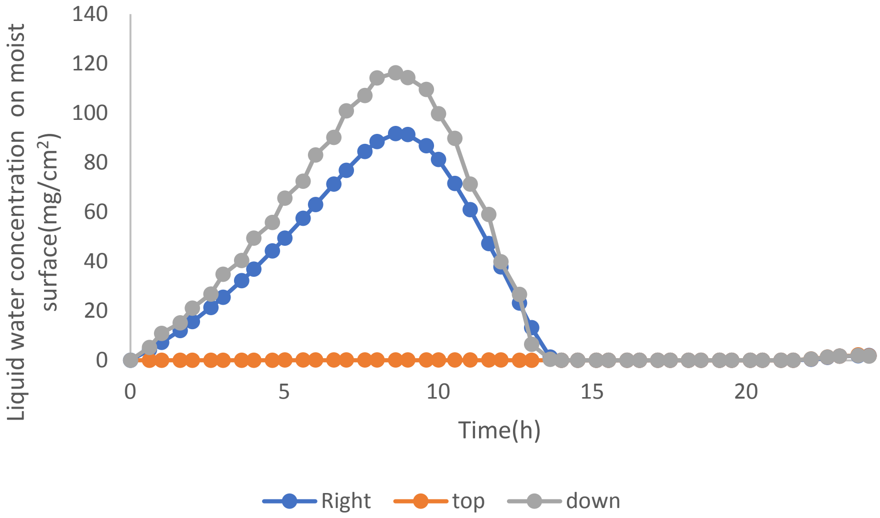


Figure 9. Changes of water vapor condensation on the surfaces of the electronic enclosure over time (case of two holes).

b) The case of three holes

The modeling done in this section includes three holes; one hole is placed on the left side of the enclosure, and the second and third holes are placed in three positions, top-right, bottom-right, and top-bottom, respectively. Figure 10 illustrates the time-dependent moisture condensation on the internal surfaces of the electronic enclosure for three simulated configurations with three ventilation holes. The highest condensate level, approximately 134.9 mg/cm² (occurring around 8:30), corresponds to the lower-right hole placement. Conversely, the upper-right configuration exhibits the lowest condensation at about 41.6 mg/cm².The reason for this phenomenon is that in the case of having three holes, it is similar to the case of having two holes (considering that the first hole is located in a fixed place and in the upper and left position of the chamber), while the second and third holes are located at the bottom and right. The most circulation of moist air inside the enclosure occurs due to natural convection and diffusion, and as a result, the moisture condensation has the highest amount.

On the other hand, as can be seen from the comparison of Figures 8 and 9, the highest moisture condensation is related to cases with three holes, where the second and third holes are located at the bottom and right, and after that, cases with two holes, where the second hole is located at the bottom. Similarly, the lowest condensation is related to cases with two holes, when the second hole is at the top, and three-hole cases, when the second and third holes are at the top-right. In other words, the simulation results show that increased number of holes doesn't always mean more condensation: this is a very important finding. Simply adding more holes can alter the airflow patterns in ways that actually reduce condensation. If the additional holes facilitate the removal of warm, less humid air or create a flow path that bypasses critical surfaces, they can be beneficial. In essence, the location of the holes dictates the airflow pathways and the extent of mixing between the incoming ambient air and the air within the enclosure. Configurations that force the cool, moist air to circulate more thoroughly around the electronic components are more likely to lead to condensation. Adding more holes can either enhance this circulation or create pathways that reduce it, depending on their placement. Therefore, the strategic placement of a certain number of holes is more critical than simply maximizing the number of holes.

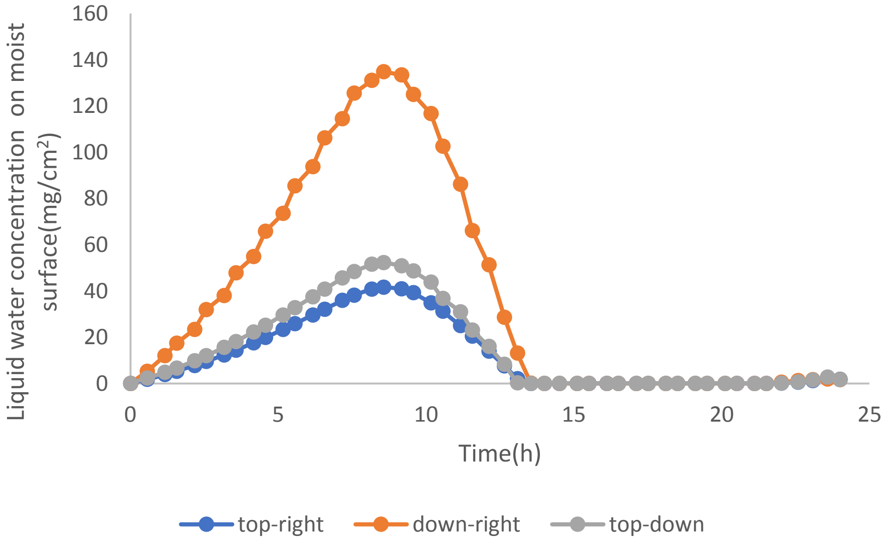


Figure 10. Changes of water vapor condensation on the surfaces of the electronic enclosure over time (case of three holes).

The effect ventilation holes size

Another effective parameter in air humidity condensation is the size of the ventilation holes created on the electronic enclosure, so in order to investigate the effect of the size of the holes, simulation was done for three geometries similar to Figure 1 with three different hole sizes, 1 mm, 6 mm, and 9 mm. Other parameters are kept constant for comparison. Figure 11 shows the amount of moisture condensed on the internal surfaces of the electronic enclosure during the time for all three simulated models. As observed around 8:30 AM, the highest moisture condensation (91.6 mg/cm²) occurs when the ventilation holes are smallest. Increasing the hole size to 6 mm and 9 mm results in a decrease in moisture condensation to 46.5 mg/cm² and 37.7 mg/cm², respectively. The reason for this phenomenon is that with the increase in the size of the holes while other parameters remain constant, the flow rate of the incoming and outgoing air from the enclosure increases and the circulation of air inside the enclosure and the possibility of mixing hot and cold air and free convection decreases (Figure 12). as a result of which moisture condensation in the enclosure is reduced.

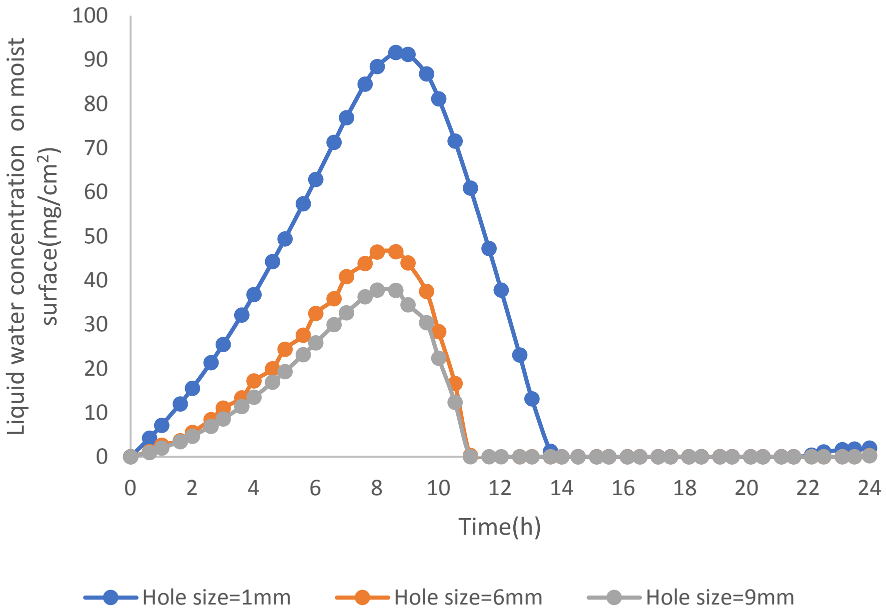
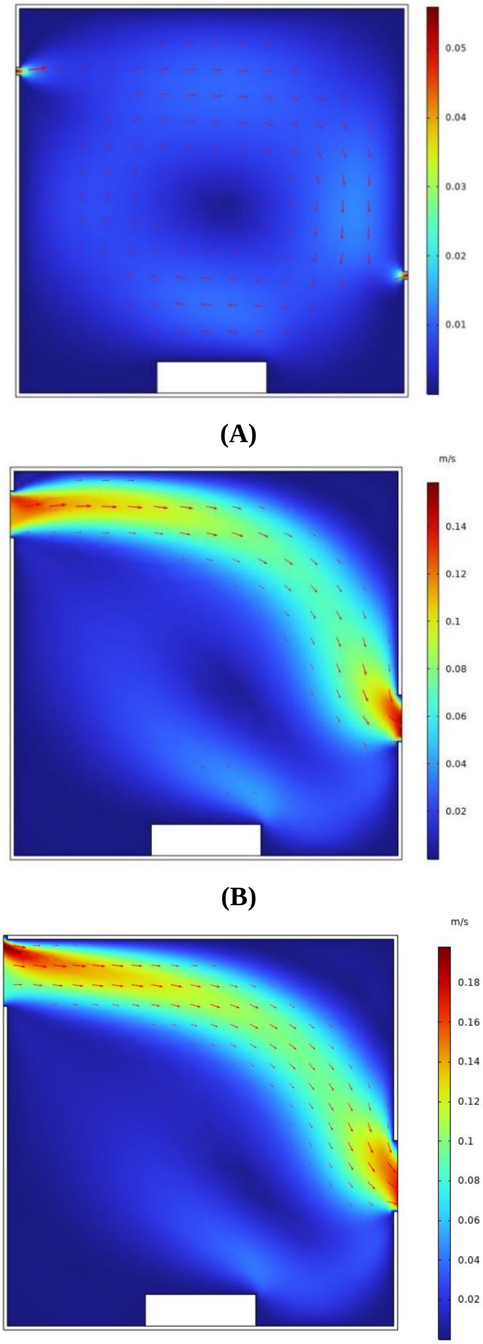


Figure 11. **Changes of water vapor condensation on the surfaces of the electronic enclosure over time for holes of different dimensions.**



(c)

Figure 12. Velocity contours for holes with different dimensions. A. Holes with size of 1mm, b. Holes with size of 6mm, c. Holes with size of 9 mm.

The effect of enclosure size

To investigate the influence of enclosure size on air humidity condensation, simulations were conducted on three square enclosures with side lengths of 50, 75, and 100 mm, maintaining other parameters constant (similar geometry to Figure 1). Figure 13 presents the time-dependent moisture condensation on the interior surfaces for these three models, revealing only minor fluctuations. Notably, doubling the enclosure size from 50 mm to 100 mm resulted in a small 2 to 3 percent decrease in condensation. This minimal change is attributed to the relatively consistent airflow within the enclosures across the three sizes, given the fixed size of the ventilation holes and other parameters.

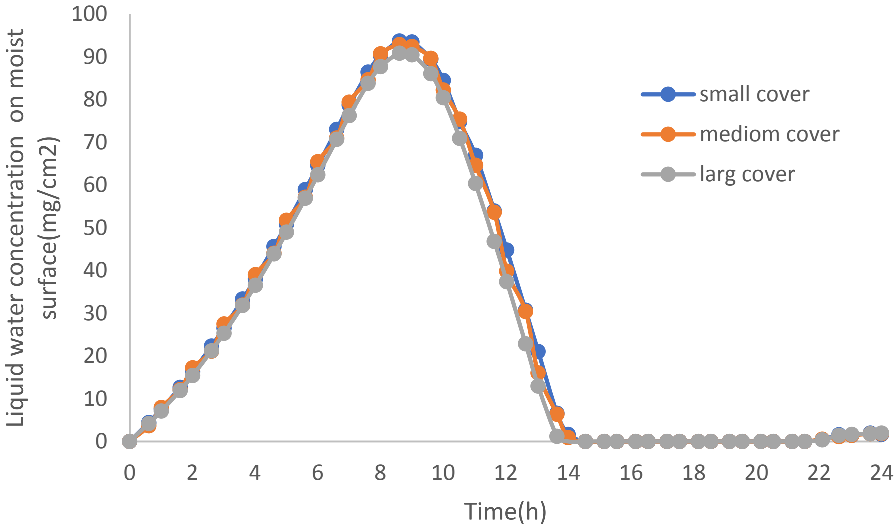


Figure 13. **Changes of water vapor condensation on the surfaces of the electronic enclosure over time for enclosures with different size.**

The effect of enclosure material

In the past, electronic enclosures were mainly made of metals, but today, polymers are used due to their light weight, ease of processing and assembly, better aesthetic design options, and greater affordability [32]. In this study examined the effect of enclosure material on moisture condensation by simulating three electronic board models with polystyrene, aluminum, and polyvinyl chloride. Figure 14 illustrates the findings, revealing that the aluminum enclosure experienced the highest condensation rate around 8:30 AM. In contrast, the polystyrene and polyvinyl chloride enclosures demonstrated a 19.6% and 20.6% decrease in moisture condensation compared to the aluminum enclosure. One of the differences between the selected materials is the conductivity heat transfer coefficient, which is the highest in the case of aluminum, and therefore the cooling of the enclosure in this case is more than in other cases, and of course, the moisture condensation is also higher. Therefore, according to the obtained results, it can be said that it is better to use polymer materials for areas with high air humidity, and for other areas, it is more suitable to use aluminum and similar items.

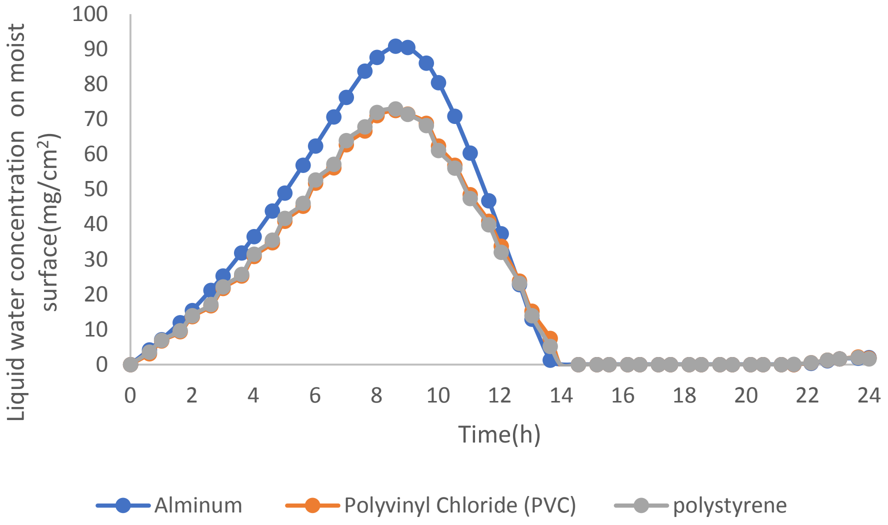


Figure 14. **Changes of water vapor condensation on the surfaces of the electronic enclosure over time for enclosures with different materials**

Conclusion

This research has provided a comprehensive numerical investigation into the critical issue of moisture condensation within electronic enclosures and its implications for the reliability of enclosed electronic boards. By simulating a range of enclosure designs and material choices under realistic environmental conditions, specifically contrasting humid (Nowshahr) and dry (Tabriz) climates, this study yields actionable insights for mitigating condensation risks. Findings underscore the significant impact of high ambient humidity, demonstrating prolonged periods of near-saturation within enclosures in humid environments, which elevates the potential for failure mechanisms like corrosion and electrical malfunction. Crucially, the strategic placement of ventilation holes emerged as a key design parameter. Positioning ventilation openings at the top of the enclosure consistently demonstrated the most effective reduction in condensation. Conversely, simply increasing the number of ventilation holes proved to be an ineffective, and potentially detrimental, strategy if not carefully considered, as certain configurations amplified condensation. Furthermore, the size of the ventilation holes exhibited a clear inverse relationship with condensation levels, with larger openings promoting airflow and reducing moisture buildup. The choice of enclosure material also presented a significant avenue for condensation control. Notably, polymeric materials, specifically polystyrene and polyvinyl chloride, offered a substantial advantage in humid environments, achieving a 19-21% reduction in condensation compared to aluminum enclosures. This difference is attributed to the lower thermal conductivity of polymers, which minimizes surface cooling below the dew point. In contrast, the overall size of the enclosure within the tested range (50-100 mm side length) exhibited a relatively minor influence on condensation.

Nomenclature Table

Symbol	Definition	SI Unit
u	Fluid velocity vector	m/s
p	Pressure	Pa
ρ	Density	kg/m^3
μ	Dynamic viscosity	Pa·s
I	Unit matrix	-
g	Gravitational acceleration vector	m/s^2
β	Thermal expansion coefficient of the moist air	1/K
T	Temperature	K
Cp	Specific heat capacity at constant pressure of the moist air	J/(kg·K)
t	Time	s
k	Thermal conductivity of the moist air	W/(m·K)
Q	Heat generated by internal heat sources	W/m^3
Q_H	Enthalpy diffusion term due to humidity gradients	W/m^3
q	Heat flux vector	W/m^2
q_0	Convective heat flux	W/m^2
h	Convective heat transfer coefficient	W/(m^2·K)
T_{ext}	External temperature	K
Q_{vd}	Viscous dissipation term	W/m^3
τ	Viscous stress tensor	Pa
Q_P	Pressure work term	W/m^3
Cp,v	Specific heat capacity at constant pressure of water vapor	J/(kg·K)
Cp,a	Specific heat capacity at constant pressure of dry air	J/(kg·K)
ω_v	Mass fraction of water vapor	-
$\mathbf{g}_w$	Vapor flux due to diffusion	kg/(m^2·s)
D	Vapor diffusion coefficient	m^2/s
M_v	Molar mass of water vapor	kg/mol
M_a	Molar mass of dry air	kg/mol
p_v	Partial pressure of water vapor	Pa
ϕ_W	Relative humidity	-
C_{sat}	Constant related to saturated vapor concentration	kg/m^3
A,B	Empirical constants for saturated vapor pressure equation	K, K
G	Moisture source term	kg/(m^3·s)

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