UNIVERSITY OF TORONTO
FACULTY OF APPLIED SCIENCE & ENGINEERING
Centre for Advanced Coating Technologies

GVA Lighting, Inc.

Condensation Project

Final Report

A. Khakpour, M.J. Gibbons, S. Chandra

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Abstract

The objective of this project is to develop a model to calculate the relative humidity within an LED enclosure for various climate conditions. Condensed water vapour within an LED unit may lead to permanent damage to the units printed circuit board. The developed model determines the internal relative humidity of the LED enclosure based on the climate data file and the LED units operative schedule.

A vent is located on the back of the LED enclosure to allow pressure relief. This membrane is permeable and allows the passage of water vapour through it. Once the local relative humidity within a unit reaches 100%, condensation will occur. The amount of vapour permeating through the vents is dependent on the vent's physical properties. An experimental investigation was performed to characterize the vapour permeability coefficient for the vent at the University of Toronto. These results were then applied to develop an equation to calculate the flow rate of moisture through the permeable membrane, based on the ambient and internal conditions.

Next, the LED unit was tested in an environmental chamber at GVA. For a given ambient relative humidity and temperature, both the vent's permeability and the internal temperature of the chamber are required to accurately calculate the relative humidity within the enclosure. Using the environmental chamber at GVA, the internal temperature and relative humidity of the LED were recorded to study moisture transfer for various climate and operative settings. Environmental tests at a constant humidity were conducted to study the thermal profile of the LEDs at different ambient temperature during operation. This knowledge further enhanced the accuracy of the developed model.

The developed model was validated using experimental data, an average error of less than 20% for relative humidity and 3% for temperature were noted. The model is computationally efficient and can be simply adapted for different vents or LED units. The model assumes a clean vent and stagnant ambient airflow with no external convection. During natural operation, the vent can become partially clogged due to pollution, contamination and droplet nucleation within their structure, changing its permeability. Therefore, simulation uncertainty may increase during the vent lifecycle.

Introduction

The purpose of this project is to evaluate the risk of condensation within the GVA® LED housings shown in Fig. 1. The humidity in the enclosure will be calculated using the climate data file and the LED operation schedule.

Figure 1. GVA Lighting Inc. LED unit that was studied for the condensation project.

During operation, when the unit is powered on, a considerable portion (~60%) of the LED power is dissipated as heat, which results in a temperature rise within the enclosure. This increase in temperature can result in a pressure build-up in the sealed enclosures, The VE80308 series Gore-Tex® vent on the back of the LED units are installed to act as a pressure relief mechanism. These fabric vents are permeable and allow water vapour to diffuse into the unit. When the relative humidity within the LED housing reaches the saturation point (100%), condensation is expected to occur. Condensed water can damage the LED's printed circuit board, shortening its the lifespan.

The mass flow rate of moisture passing through a membrane is dependent on its permeability coefficient, and the difference between moisture concentrations on the two sides of the membrane. To obtain the moisture permeability properties of the GORE-Vent an apparatus was designed and built, and an experimental investigation was conducted at the University of Toronto.

To calculate the humidity concentration, the relative humidity and temperature of the enclosure must be known. A psychometric chart can be used to convert relative humidity into humidity concentration at a given temperature. The external humidity concentration is calculated from the temperature and relative humidity data from the climate data file. To determine the internal humidity concentration the internal chamber temperature is required, As noted, previously this temperature is dependent on the external temperature and the LED operative schedule. Experiments were performed in a controlled environment chamber to characterise the internal thermal profile of the LED unit for varied ambient conditions. A correlation was generated to predict the internal temperature based on the ambient temperature and operation status of the light.

The experimental findings on the moisture permeability properties and the LED's internal temperature profile were used to develop an algorithm to calculate the amount of moisture transfer across the permeable membrane on an hourly basis using the climate data file supplied by GVA.

To further study the internal humidity response of the LED to complex climate conditions and temperature fluctuations, multiple longer-term experiments were performed in the controlled environmental chamber at GVA. Results from these experiments were used to modify the algorithm and improve the model accuracy.

In this report, the theory of moisture diffusion through textiles is introduced; the methodology of evaluating the moisture permeability coefficient of the Gore-Tex® fabric vent is described, and experiments along with the results are reported. The model that was developed to simulate to calculate the internal relative humidity of the LED enclosure is described, validated, and the sources of error are discussed.

Background and Theory

List of Parameters

The variables that are used in this section, along with their notation and units are described in Table 1.

Table 1. List of variables used in the report

Parameter	*Notation*	*Unit*	*Note*
Volume	**V**	[m^3]	
Area	**A**	[m^2]	
Thickness	**L**	[m^1]	
Water vapour concentration (humidity concentration) (moisture concentration)	**Cv**	[g/m^3]	**Cv_{int}:** Internal vapour concentration (refers to LED's internal conditions) **Cv_{ext}:** External vapour concentration (refers to ambient conditions) **ΔC:** Difference between internal and external vapour concentrations
Water vapour concentration rate of change	**$\dot{C}v$**	[$g/m^3.s$]	**$\dot{C}v_{int}$:** Rate of change of water vapour concentration in the internal chamber
Time	**t**	[s]	
Characteristic water vapour permeability coefficient	**Γ**	[1/s]	Depends on material type and fabric structure only (per unit area and per unit thickness)
Effective water vapour permeability coefficient	**K**	[m/s]	Depends on material type and fabric structure as well as physical properties (area and thickness)
Effective water vapour permeability coefficient per unit area	**Ķ**	[1/m.s]	Depends on material type and fabric structure for the thickness of VE8 series vents (per unit area)
Mass flow rate	**ṁ**	[g/s]	**$\dot{m}_v$:** water vapour mass flow rate **$\dot{m}_l$:** water liquid mass flow rate

Theory of Vapour Passage Through GORE® Vents

A schematic view of the LED enclosure and vent is shown in Fig. 2. The chamber has an internal volume (*V*), a fabric vent of an active area (*A*) and thickness (*L*) installed on the top hole. Moisture passage through the vent is dependent on the internal (Cv_{int}) and external (Cv_{ext}) humidity concentrations, with moisture flowing from the high concentration to low.

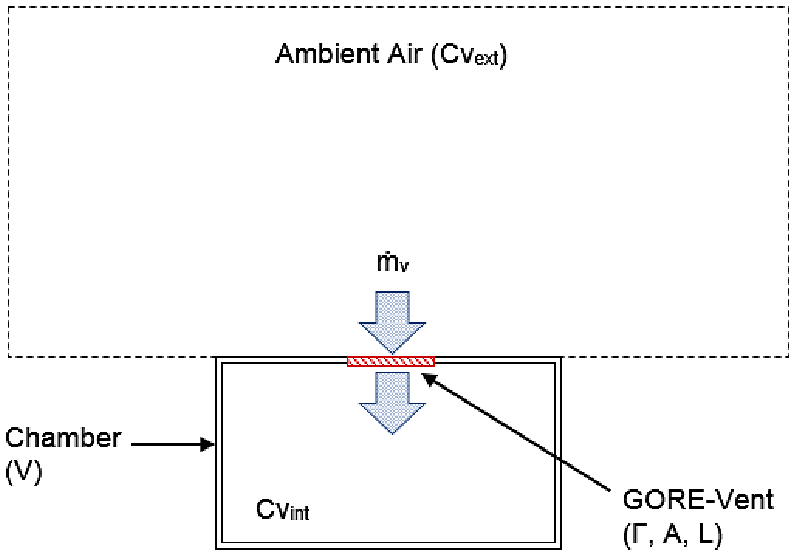

Figure 2. Schematics of a vented chamber exposed to outdoor conditions.

The mass flow rate of water vapour through the vent can be found from Eqn 1.

$$\dot{m}_v = \frac{d}{dt}(V.\mathrm{Cv}_{int}) \qquad \text{Eqn. (1)}$$

Since the vapour diffuses through the fabric vent, the mass permeability equation may be used to compute the flow rate of moisture. The flow rate of vapour depends on the characteristic permeability coefficient of the vent (Γ) (which is independent of vent size and thickness) using Eqn. 2 [1].

$$\dot{m}_v = \frac{\Gamma A}{L}(\mathrm{Cv}_{int} - \mathrm{Cv}_{ext}) \qquad \text{Eqn. (2)}$$

The terms that are dependent on the physical properties of the vent can be grouped and termed the effective permeability coefficient (*K*) as shown Eqn. 3.

$$K = \frac{\Gamma A}{L} \qquad \text{Eqn. (3)}$$

Both Eqns 1 and 2 can be equated to yield Eqn. 4.

$$\frac{d}{dt}(V.Cv_{int}) = K(Cv_{int} - Cv_{ext}) \qquad \text{Eqn. (4)}$$

Eqn. 4 may be re-arranged to obtain the permeability coefficient K, as shown in Eqn. 5.

$$K = \frac{\frac{d}{dt}(V.Cv_{int})}{Cv_{int} - Cv_{ext}} \qquad \text{Eqn. (5)}$$

Both the nominator and denominator of the Eqn. (5) can be calculated from the experimental data. As the volume of the chamber is constant Eqn. 6 yields.

$$K \approx \frac{\frac{\Delta(V.Cv_{int})}{\Delta t}}{(Cv_{int} - Cv_{ext})} \approx \frac{V \times \Delta(Cv_{int})}{\Delta t\,(Cv_{int} - Cv_{ext})} \qquad \text{Eqn. (6)}$$

In this case, K/V is the slope that relates the rate of change in the internal vapour concentration to the difference in vapour concentrations in the two environments (Eqn. 7)

$$\frac{\Delta(Cv_{int})}{\Delta t} = \left(\frac{K}{V}\right)(Cv_{int} - Cv_{ext}) \qquad \text{Eqn. (7)}$$

Using Eqn 7 and measuring the internal and external vapour concentrations of the setup, the effective permeability coefficient of the Gore-Vent is experimentally determined.

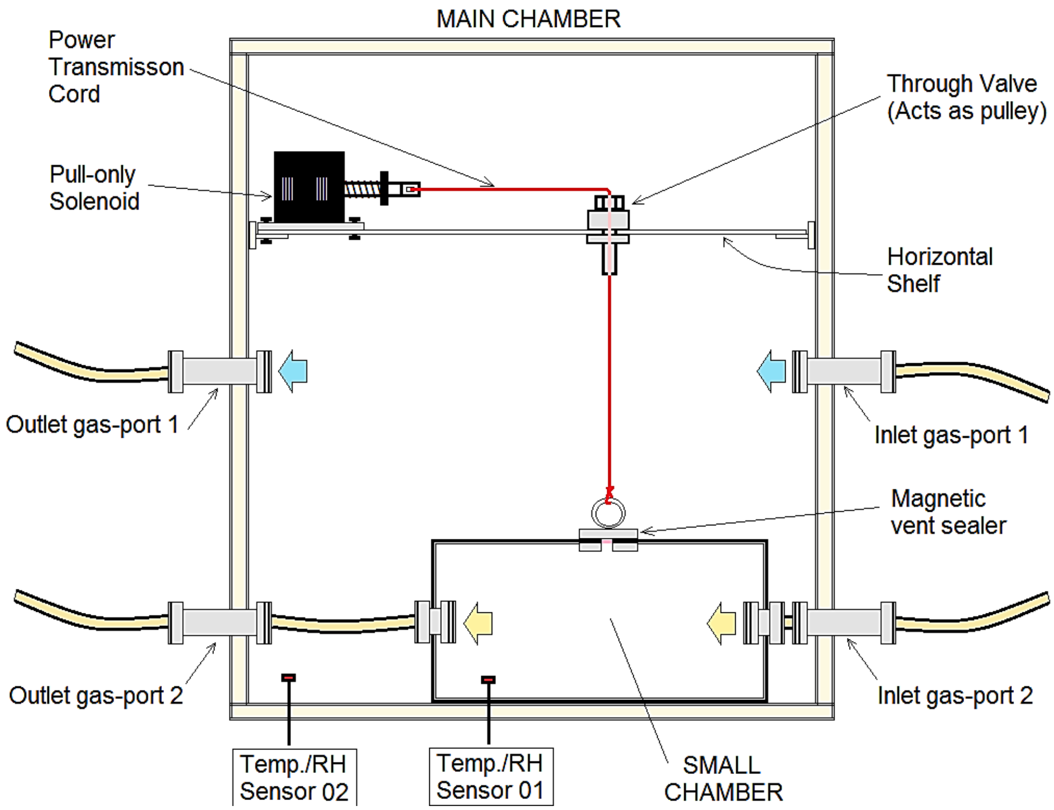

Figure 3. Schematic view of the moisture permeability testing apparatus

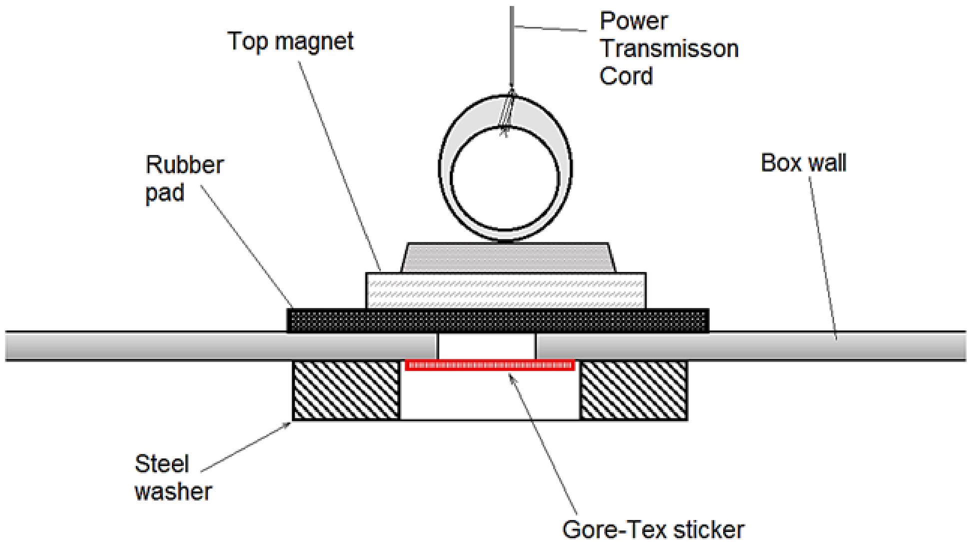

Figure 4. Sealed magnetic lid covers the vent without having any contact with the Gore-Tex sticker (red)

Experimental Setup

Permeability coefficient characterization

Fig. 3 shows a schematic of the experimental facility employed in the first stage of testing carried out at the University of Toronto. The facility consists of a large external chamber. Inside this chamber, a smaller chamber is placed, this smaller chamber is representative of a LED unit. On this smaller chamber, a hole and vent are placed (see Fig. 3 and 4). Prior to the start of testing both chambers are isolated from each other using a magnetic seal (Fig. 4). The larger chamber is feed high humidity air (80-90%) by filtering the air inlet line with several stages of bubblers, shown in Fig. 5. While desiccant is implemented on the inlet line of the smaller chamber to establish a low humidity (10-20%) environment. The relative humidity and temperature of each chamber are monitored using an Omega sensor (Omega, P/N: HX94B). The vent used in this study was a larger variant (VE8 series, P/N: VE81221) of the VE8 series used on the GVA LED units. This was chosen to ensure a reasonable experiment length. The vent had an active venting area of 122.7mm^2, roughly 14.4 times larger than the ones used in the GVA LED unit. At the start of testing the solenoid actuator (Fig. 3) is activated and pulls the sealed magnetic lid (Fig. 4), exposing the fabric vent.

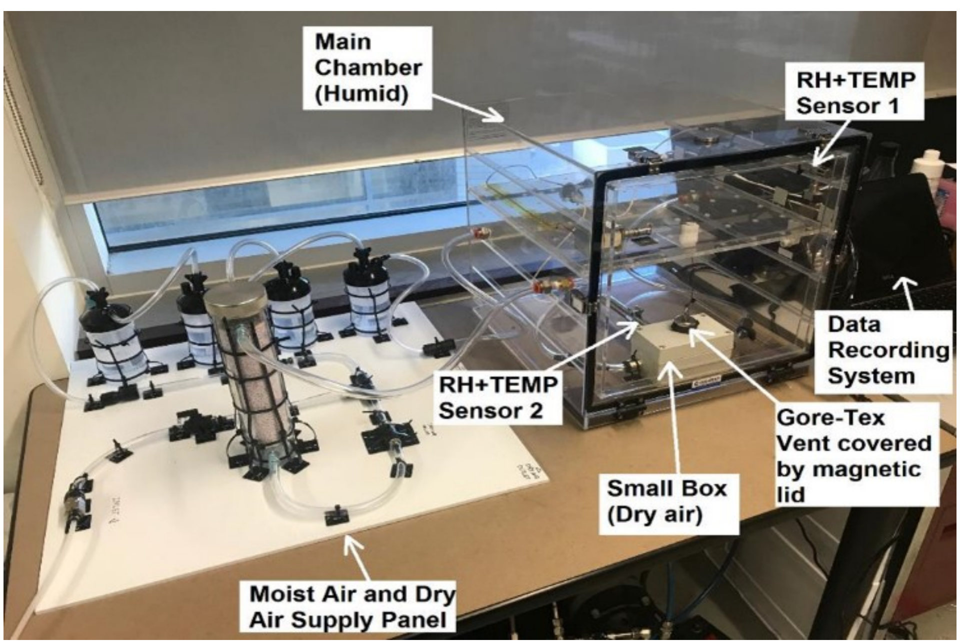

Figure 5. Actual setup that was used for vent permeability characterization experiments

GVA Environmental Chamber Experiments

The temperature inside the LED chassis rises above the ambient temperature once the LED unit is switched on. Changing internal temperatures can affect the relative humidity, as the hotter air can hold more moisture, than colder air. Additionally, temperature gain and loss of the LED units during switch-on and switch-off transient periods may result in changes of air pressure within the LED chassis due to the air's thermal expansion and contraction. The pressure relief vent on the unit balances the airflow until the internal air pressure reaches equilibrium with the ambient air pressure. This thermally induced airflow through the vent may also contribute to a transfer of moisture. To investigate the pattern of moisture transfer while turning the lights on and off, and to study the relative humidity changes inside the LED unit in a changing climate, a series of experiments were conducted.

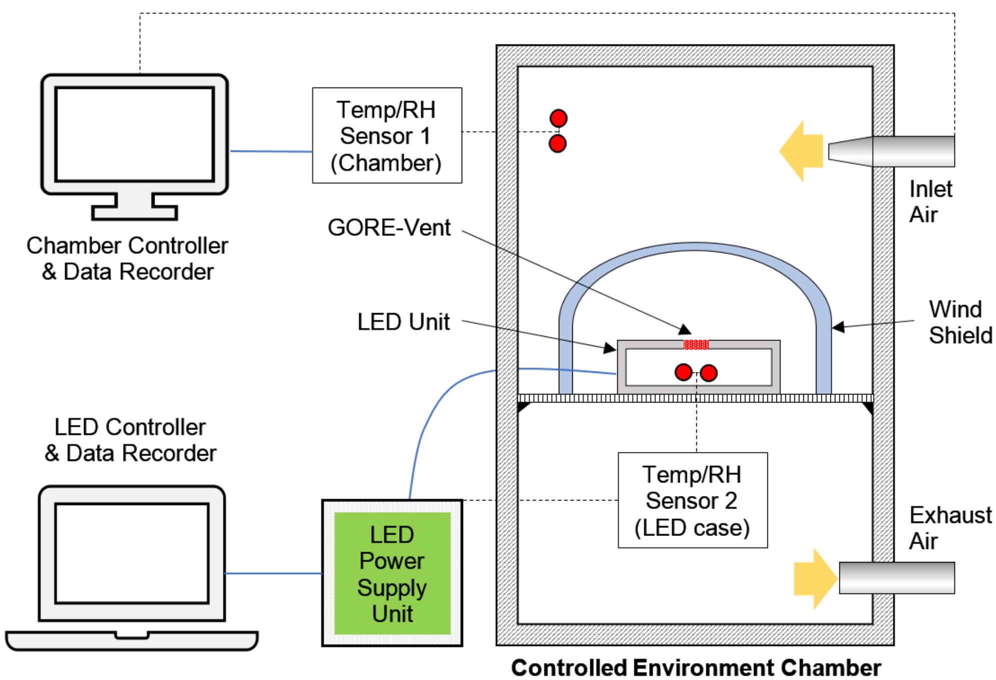

Figure 6. A schematics of the environmental test setup

A GVA LED unit was placed in a controlled environment chamber and was subject to various controlled climate profiles to study its internal humidity response in different ambient and operative setting. The LED unit was placed face down, in order to have the vent fully exposed on the top side. The power and communications cables were routed out of the chamber to the LED power supply unit and data acquisition laptop respectively (Fig. 6). The GVA software on the laptop controlled the LED units output power and collected the climate data from the sensor. The environmental chamber was programmed for a specified temperature and humidity profile and the climate data was recorded every 60 seconds. Since the air inside the chamber was not stationary and to minimize the effects of the convective transfer of moisture, a shield was placed over the LED. Once an experiment ended, the chamber was shut down and the temperature and relative humidity data for both the LED and chamber were exported. The exported data was then processed

In tandem with validating the permeability results from the University of Toronto test, the thermal profile of the LED unit was characterized. To calculate the internal vapour concentration within the LED unit both relative humidity and temperature are required. The internal temperature of the unit is dependent on the external ambient temperature and the power state of the LED unit. Several experiments were conducted to develop a correlation to determine the LED internal temperature as a function of the ambient temperature and the power dissipated.

Data processing methodology

Moisture diffuses from an environment with a higher humidity concentration, into the environment with lower moisture concentration [1]. From Eqn. (2) it was shown that the diffusive mass flow rate depends on the difference between the humidity concentrations of the two environments. As a result, relative humidity data alone cannot be used to compute the permeability coefficients from Eqn. 6. To characterize the permeability behaviour of the Gore-Tex vents, raw data was converted to humidity concentration, using a psychrometric function [2].

Fig. 7a shows a sample set of data acquired from the first stage of testing from the University of Toronto. Fig. 7b shows the calculated vapour concentration of each environment. In this case, the internal and external chamber temperatures are held constant, as a result, the trend of both sets of data is mirrored.

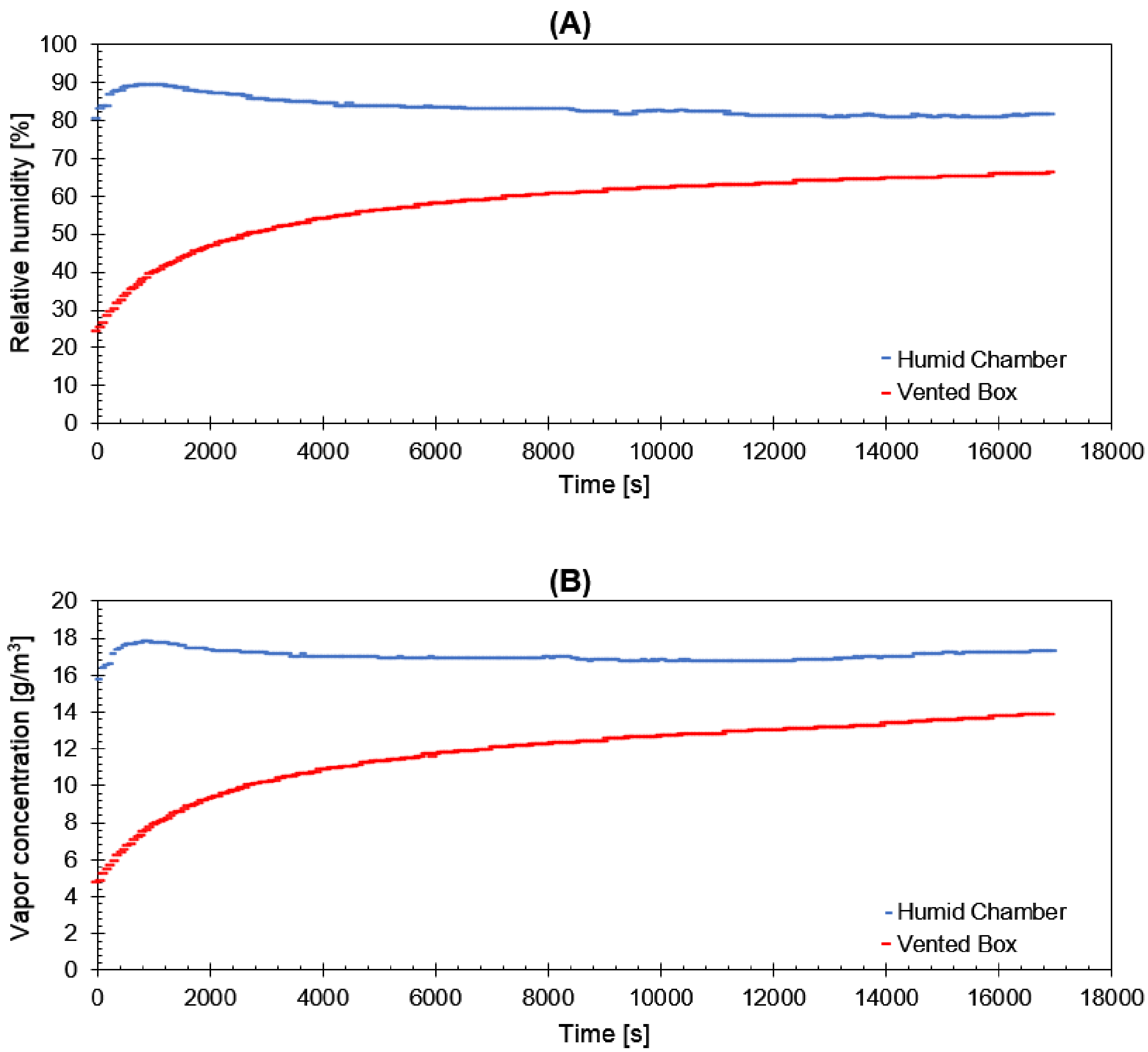

Figure 7. (A) Relative humidity profile (B) Humidity concentration profile after processing the relative humidity and temperature data.

After processing the sensors data and obtaining the humidity concentrations for every time step, an Excel table was developed that contains the vapour concentrations for the vented box and humid chamber for the duration of the experiment. The difference between the vapour concentrations in two environments was also calculated for each timestep and was placed in the Excel table. Finally, the rate of gain of vapour concentration in the vented box was calculated for each timestep and input into the last column of the table. Table 2 shows the format of the table that is used to process the data for the diffusion study.

Table 2. The format of the table that the experimenters used to study the moisture diffusion through the Gore-Tex vents.

Time [s]	**Humid chamber's vapour concentration Cv_{ext}, [g/m^3]**	**Vented chamber's vapour concentration Cv_{int}, [g/m^3]**	**Difference between vapour concentration of the two environments $\Delta C = Cv_{ext} - Cv_{int}$, [g/m^3]**	**Rate of gain of vapour concentration in the vented box $\dot{C}v_{int}$, [g/m^3.s]**
t-01	C(ex) – 01	C(in) – 01	[C(ex) – 01] – [C(in) – 01]	N/A
t-02	C(ex) – 02	C(in) – 02	[C(ex) – 02] – [C(in) – 02]	$\frac{[C(in) - 02] - [C(in) - 01]}{\Delta t}$
t-03	C(ex) – 03	C(in) – 03	[C(ex) – 03] – [C(in) – 03]	$\frac{[C(in) - 03] - [C(in) - 02]}{\Delta t}$
t-04	C(ex) – 04	C(in) – 04	[C(ex) – 04] – [C(in) – 04]	$\frac{[C(in) - 04] - [C(in) - 03]}{\Delta t}$
t-05	C(ex) – 05	C(in) – 05	[C(ex) – 05] – [C(in) – 05]	$\frac{[C(in) - 05] - [C(in) - 04]}{\Delta t}$
t-06	C(ex) – 06	C(in) – 06	[C(ex) – 06] – [C(in) – 06]	$\frac{[C(in) - 06] - [C(in) - 05]}{\Delta t}$

The last two columns of this table can be plotted against each other to obtain the relationship between the rate of gain of moisture in the vented box and the difference between vapour concentrations in the two environments. Fig. 8 shows a sample plot of the said parameters. Based on the theory of mass diffusion and Eqn. 7, the slope of a curve fit through the data corresponds to the effective permeability coefficient divided by the volume of the box (K/V).

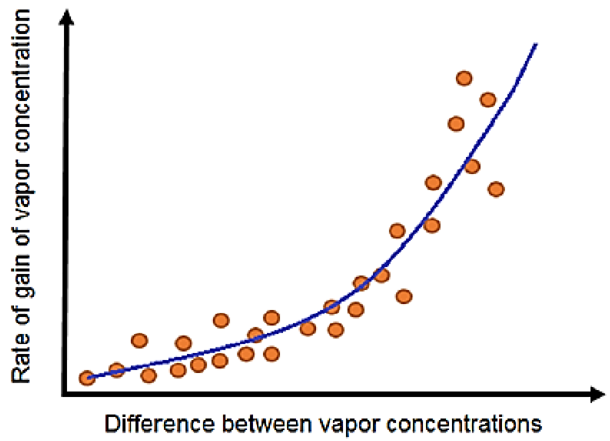

Figure 8. A schematic outline of the plot of the difference between vapour concentrations vs. the rate of gain of vapour concentration in the vented box.

Experiments and Results

GORE® Vent Characterisation Experiments - UofT

Three experiments were performed to analyze the vapour diffusivity behaviour of the fabric vent and confirm the repeatability. Once the lid on the vent was lifted and vapour diffusion into the small chamber began, humidity and temperature data were recorded by both sensors once every minute. Raw data was then processed, and a psychometric calculator embedded in an Excel file was utilized to calculate the water vapour concentrations at every time step. For every data point, the rate of water concentration buildup was calculated and plotted against the difference in concentrations of the two chambers (Fig. 9).

To investigate the impact of repeated exposure of the vent to a humid environment. A fourth test was conducted immediately following the third permeability characterisation test. It was observed that the moisture diffusion rate reduced noticeably by roughly 35 to 50% (Fig.10). It is believed that this reduction is possibly due to an occurrence of partial clogging that is likely caused by droplet condensation within the fabric structure. However, more research needs to be done to confirm this phenomenon, which is outside the scope of the project.

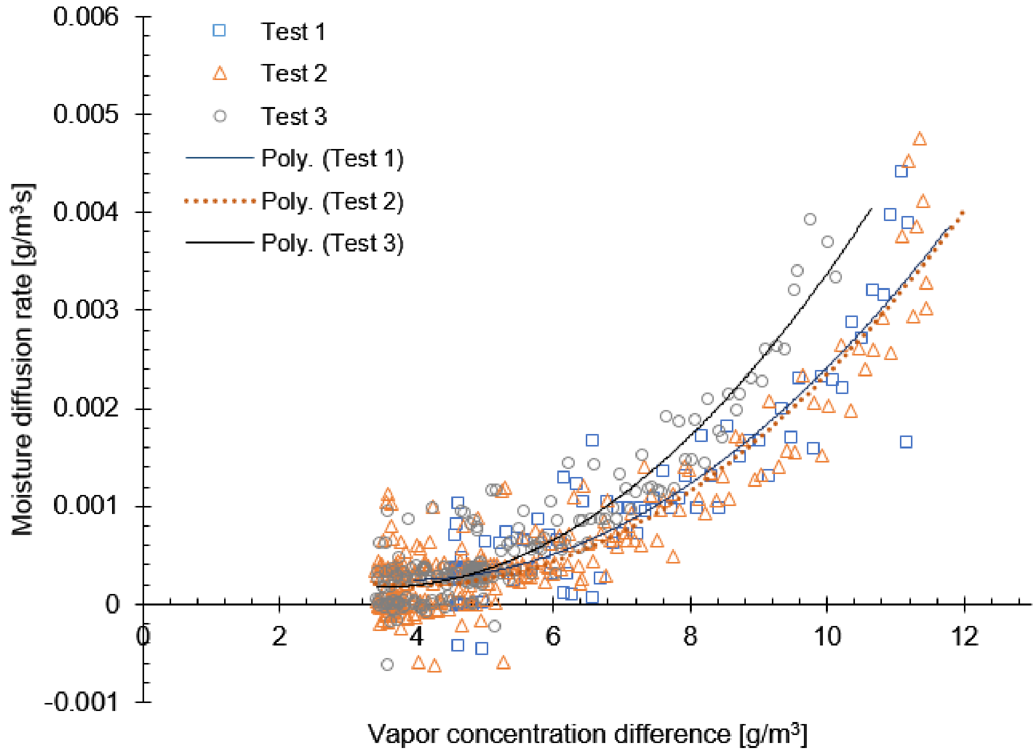

Figure 9. Moisture concentration buildup rate through the Gore-Tex sticker as a function of moisture concentration difference between the external and internal environments.

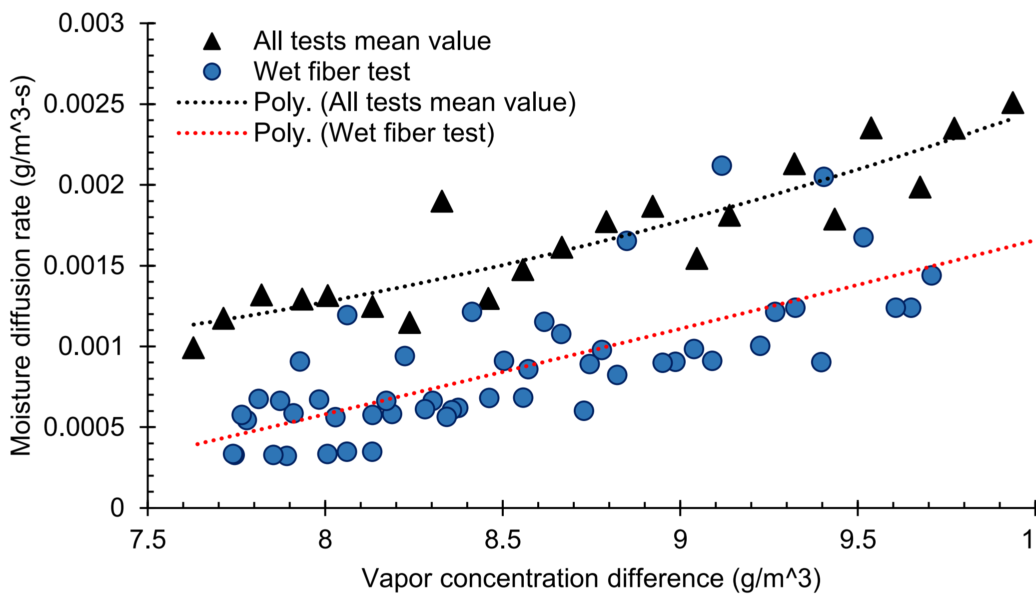

Figure 10. Comparison between the moisture diffusion rate through a dry Gore-Tex vent and a vent exposed to high humidity conditions.

Environmental Chamber Experiments - GVA

Several controlled environmental experiments were planned and performed, each of which pursuing an objective of their own. After completion of one experiment, the raw data was processed, and the internal and external vapour concentration data were analyzed. Based on the finding of each experiment, and to investigate the findings in more detail, the next experiment was planned accordingly.

First Experiment (GVA-01)

The objective of this experiment was to verify and compare the moisture passage rates through the Gore-VENT and into the LED unit, to those values that were obtained earlier in the Gore-Tex vapour permeability characterization experiments.

In this experiment, the LED unit was exposed to the specified climate profile (Fig. 11) for a duration of 48 hours. The LED unit was switched off and the chamber's temperature was set equal to the room temperature. In the beginning, the chamber's relative humidity was immediately ramped up to 95% and was held constant for 24 hours. After 24 hours, relative humidity was quickly ramped down to 25%, and the test continued for another 24 hours. Meanwhile, the temperature and relative humidity inside the LED unit was collected as well as the environmental chamber's temperature and relative humidity.

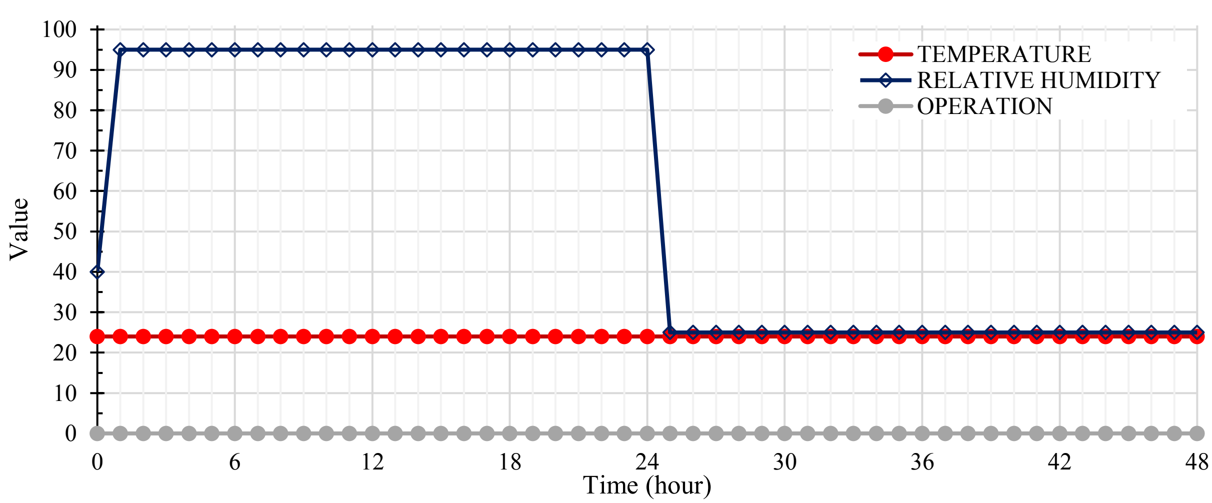

Figure 11. Climate and LED's operative specifications for the GVA-01 experiment

After completion of this experiment, relative humidity and temperature data that was acquired from the sensors were processed, converted into humidity concentration and an equation was obtained that approximates the vapour permeability coefficient as a function of the difference between the two humidity concentrations. In Fig. 12, the relative humidity trend for the environmental chamber and the LED chassis is plotted for GVA-01 testing. It can be observed that the testing length of 24 hours was not sufficient for the LED units internal relative humidity to reach the ambient conditions. The experimental relative humidity response of the LED chamber was later used to validate the computer model.

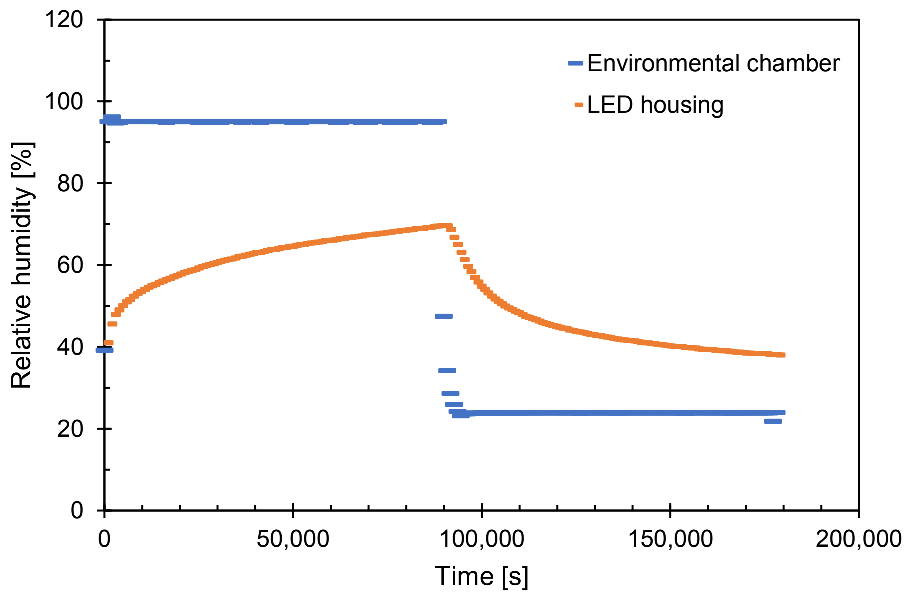

Figure 12. Relative humidity profile of the LED housing and the environmental chamber in GVA-01 testing

Second Experiment (GVA-02)

The second experiment was conducted over a longer testing period to ensure the equilibrium of the relative humidity for the internal and external chambers. This methodology enables validation of the permeability coefficient determined in the first stage of testing at UofT. The second objective of this experiment was to study the impacts of switching the LEDs on/off on the internal moisture concentration, temperature and relative humidity. In this experiment, the LED unit was exposed to a steady climate setting (Fig. 13) for the entire test duration (120 hours). The LED unit was initially switched off and the chamber's temperature and relative humidity ramped up to 45°C and 95% respectively. After 66 hours, and once the internal relative humidity reaches the chambers relative humidity, the LED was switched on. The LED was switched off at the 97th hour, and the test continued for another 24 hours. Temperature and relative humidity data inside the LED unit was collected as well as the environmental chamber's temperature and relative humidity.

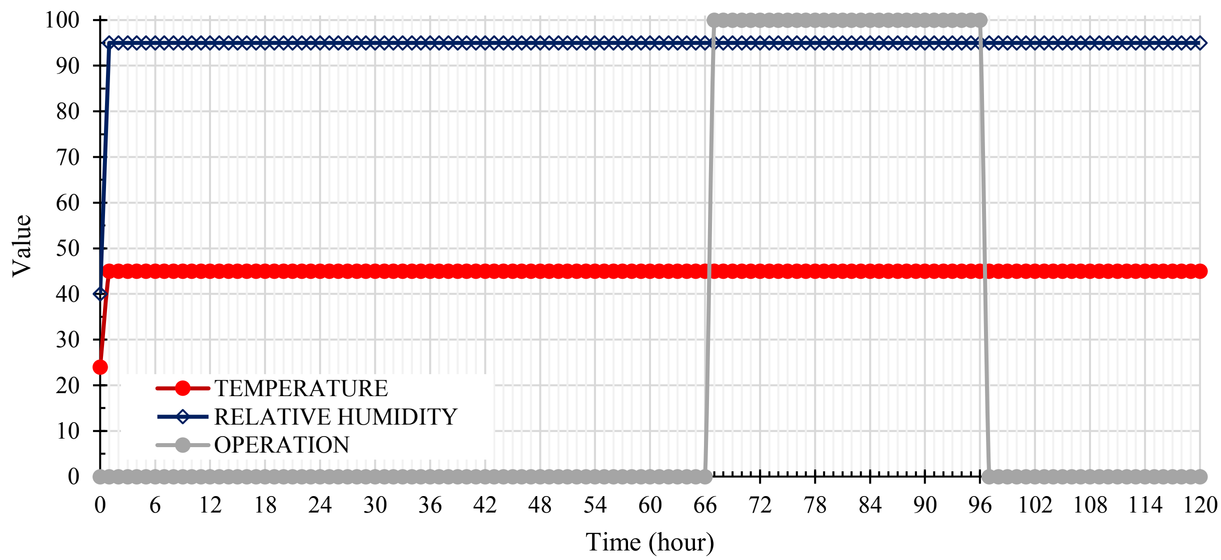

Figure 13. Climate and LED's operative specifications for the GVA-02 experiment

Fig. 14 demonstrates the rate of change of moisture concentration in the LED chassis, as a function of the internal and external humidity concentration difference. The moisture diffusion behaviour that was observed in the Gore-Tex permeability characterization experiments was verified by the GVA-01 and GVA-02 experiments, and a correlation was obtained to approximate the rate of moisture permeation through the vent. This correlation was later used in the computer program that was developed to simulate the internal relative humidity of the LED unit.

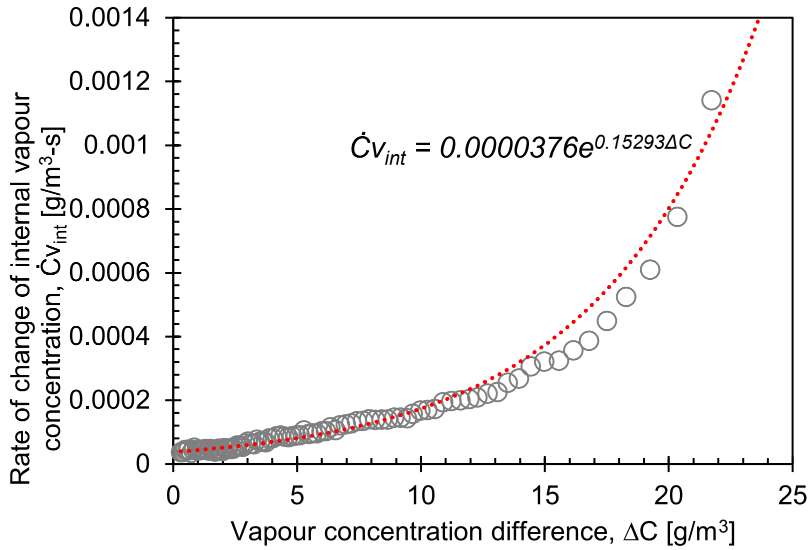

Figure 14. Moisture permeation rate through the Gore-Tex vents installed on the LED unit, as a function of humidity concentration difference of air inside and outside the LED chassis

Fig. 15 plots the relative humidity profile for GVA-02. It can be observed that once the LED was switched on, the internal relative humidity dropped rapidly due to the increasing internal temperature. The internal relative humidity is shown to increase rapidly once the LED unit is switched off. This case (high humidity environment and LED powering off) represents the situation of greatest concern to predict condensation with the LED enclosure. The uncertainty associated with the onboard GVA LED is noted by the overshoot of the internal relative humidity in comparison to the ambient chamber setting of 95%.

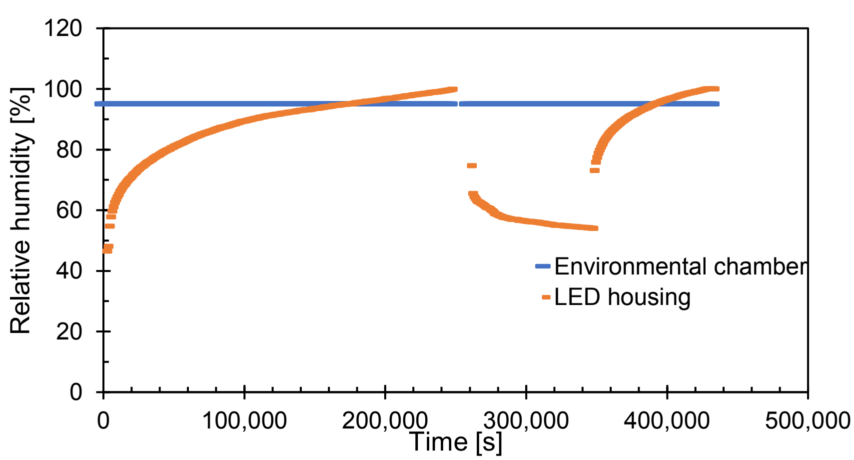

Figure 15. Relative humidity profile of the LED housing and the environmental chamber in GVA-02 testing

Another notable outcome from this test was the rapid change in moisture concentration within the LED, once the light was switched on/off (Fig. 16). This can be attributed to pressure-induced airflow through the vent during the rapid transient state of temperature gain/loss.

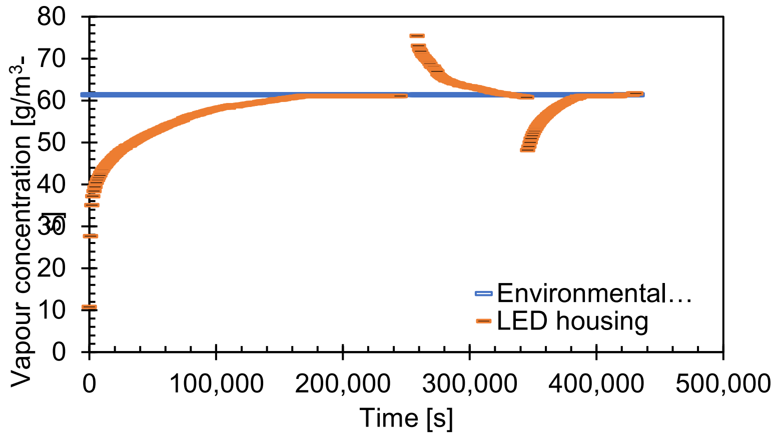

Figure 16. Moisture concentration trend of the LED housing and the environmental chamber in GVA-02 testing.

Third Experiment (GVA-03)

In this experiment, the LED unit was exposed to a complex climate profile (Fig. 17) for the duration of the test. The LED unit was initially switched off but was turned on after 16 hours. The LED remained running at full brightness for a total of 78 hours and was switched off at the 94th hour. Temperature and relative humidity data inside the LED unit were collected as well as the environmental chamber’s temperature and relative humidity.

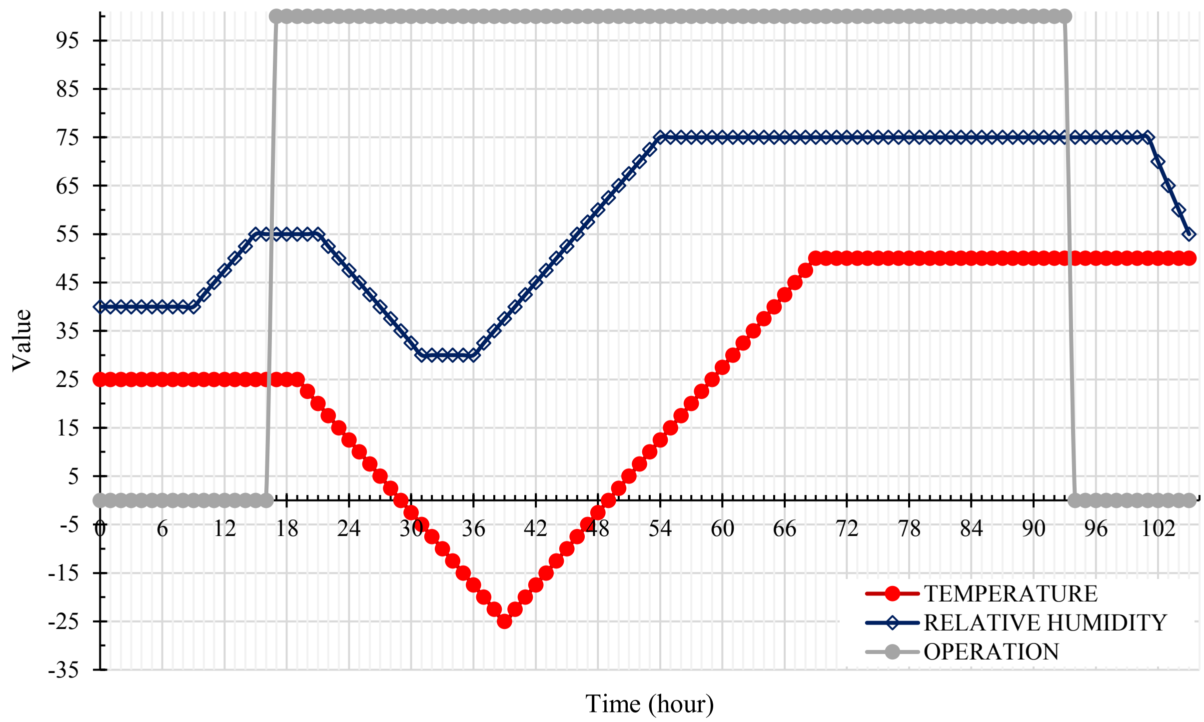

Figure 17. Climate and LED's operative specifications for the GVA-03 experiment

From the processed results, it was noted that the humidity concentration rose by about 25% once the LED was turned on and dropped by approximately 20% after the LED was switched off. This finding was consistent with the results of the GVA-02 experiment. Based on these results a correlation was developed to calculate the LED housing's internal temperature as a function of the ambient temperature when the light is in full brightness operation.

Fourth Experiment (GVA-04)

In previous experiments when the power state of the LED unit is switched (GVA-02 and GVA-03), it was observed that the moisture concentration within the LED unit changes rapidly, even though it is expected to remain constant. The goal of this experiment is to quantify this rapid gain and loss of moisture and study the possible impacts of the ambient moisture concentration on the amount of loss or gain.

In this experiment, the LED unit was exposed to a constant relative humidity of 50% for the entire testing period (Fig. 18). The external environment chamber was set to increase every 24 hours. The LED was turned on every day, stayed on for 7 to 9 hours, and then switched back off.

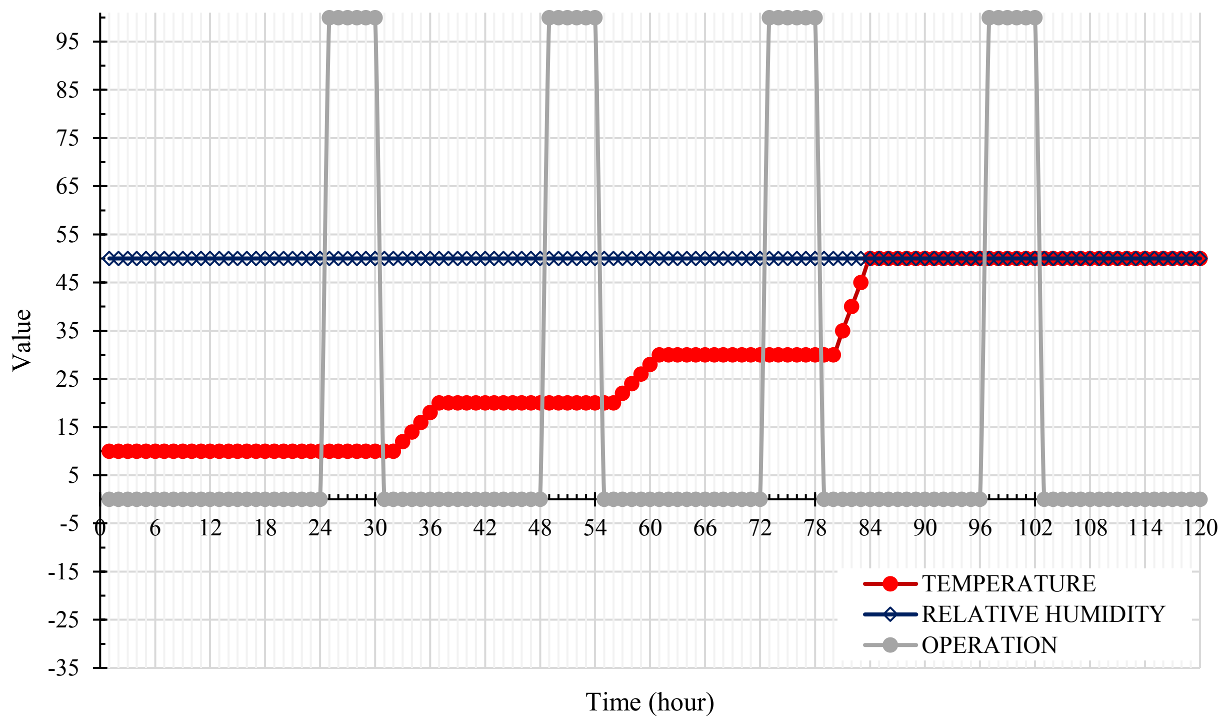

Figure 18. Prescribed climate profile and LED's operative specifications for the GVA-04 experiment

Fig. 19a plots the trend of moisture concentration during testing. It was noted that a moisture concentration change of 20 to 30% occurs immediately after LEDs switched on. The moisture gaining ratio of x1.2 to x1.3 was consistent following all the "turn-on" events regardless of the ambient humidity concentration. Similarly, a moisture concentration drop of 15 to 25% occurred after every "switch-off" event. These ratios were implemented in the computer model to improve model accuracy.

Fig.19b shows the relative humidity trend inside and outside of the LED unit during the test. When the LED light is running, it generates heat which increases the air temperature inside the LED housing. Hotter air can hold higher amounts of moisture, thus the relative humidity is reduced when the LED is powered on [2].

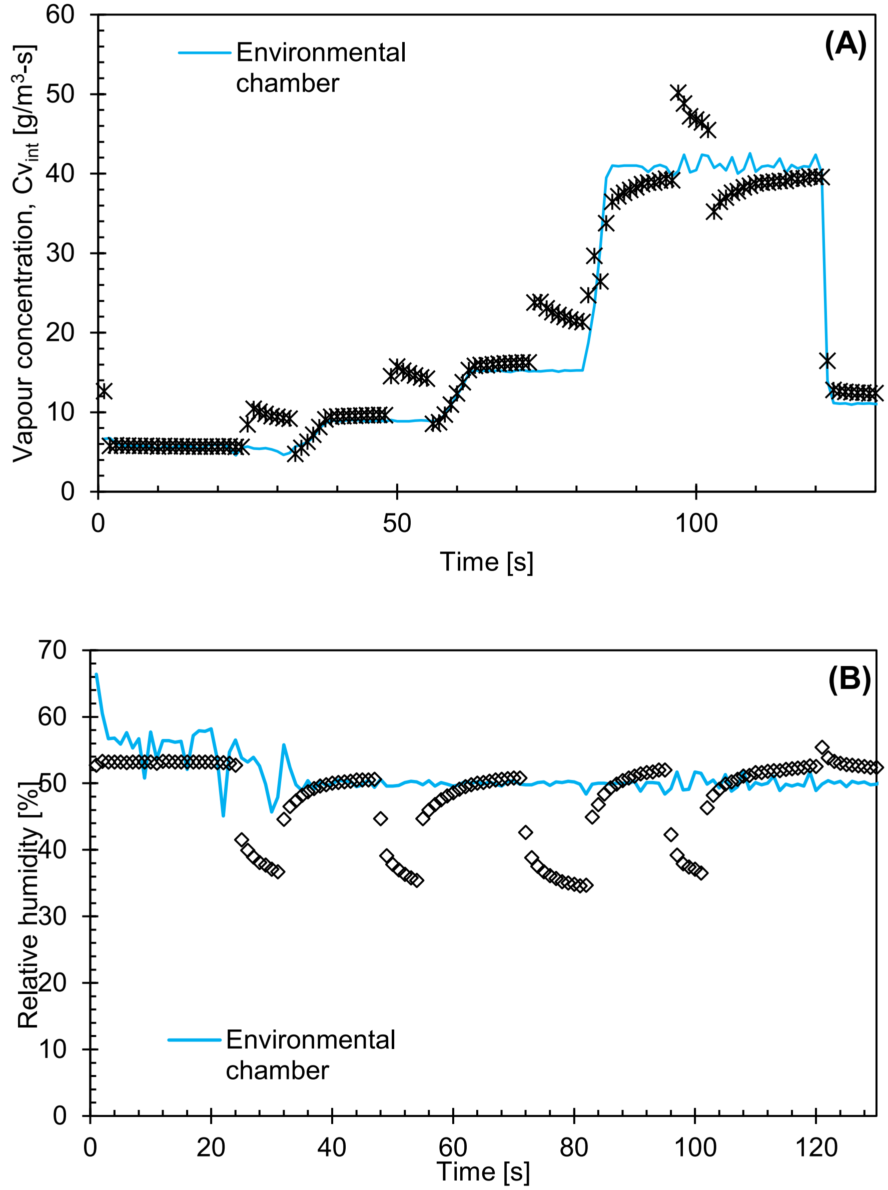

Figure 19 (A) moisture concentration trend (B) relative humidity profile of the LED housing and the environmental chamber in GVA-02 testing.

LED Thermal Profile Characterization Experiments

Three experiments were performed to investigate the thermal profile of the LED units. The first two experiments (Fig. 20a and b) were conducted using the apparatus shown in Fig. 3, aimed at obtaining the transient state thermal profile after switching the LEDs on/off. The third experiment using the GVA environmental chamber focused on studying the steady-state terminal temperature of the unit as a function of the ambient temperature (Fig. 21).

(A) Transient state thermal profile characterization experiments

The first two experiments were conducted at the University of Toronto. They were performed at two different ambient temperatures of 22^{o}C and 32^{o}C. For the first experiment the humidifier was not turned on, and the chamber's temperature was held at room temperature. For the second test, a small 50W electric coil heater was used to heat up the chamber.

Four power states were investigated for the first Full brightness, 75%, 50% and 25% brightness modes were tested separately. It was revealed that in less than 30 minutes, the LED reaches a steady-state temperature after being switched on. Similar behaviour was noted after switching the LEDs off. To acquire the thermal ramp up a profile at a given brightness level, the LED was switched on to the specified brightness and the internal temperature data was recorded once every 30 seconds, for a duration of 30 minutes. Afterwards, the LED was switched back off, and its thermal data continued to be recorded for another 30 minutes with the collection frequency unchanged. The second test was performed similarly to the first test but only for two power states (50% and 100%). The results are summarized in Table 3.

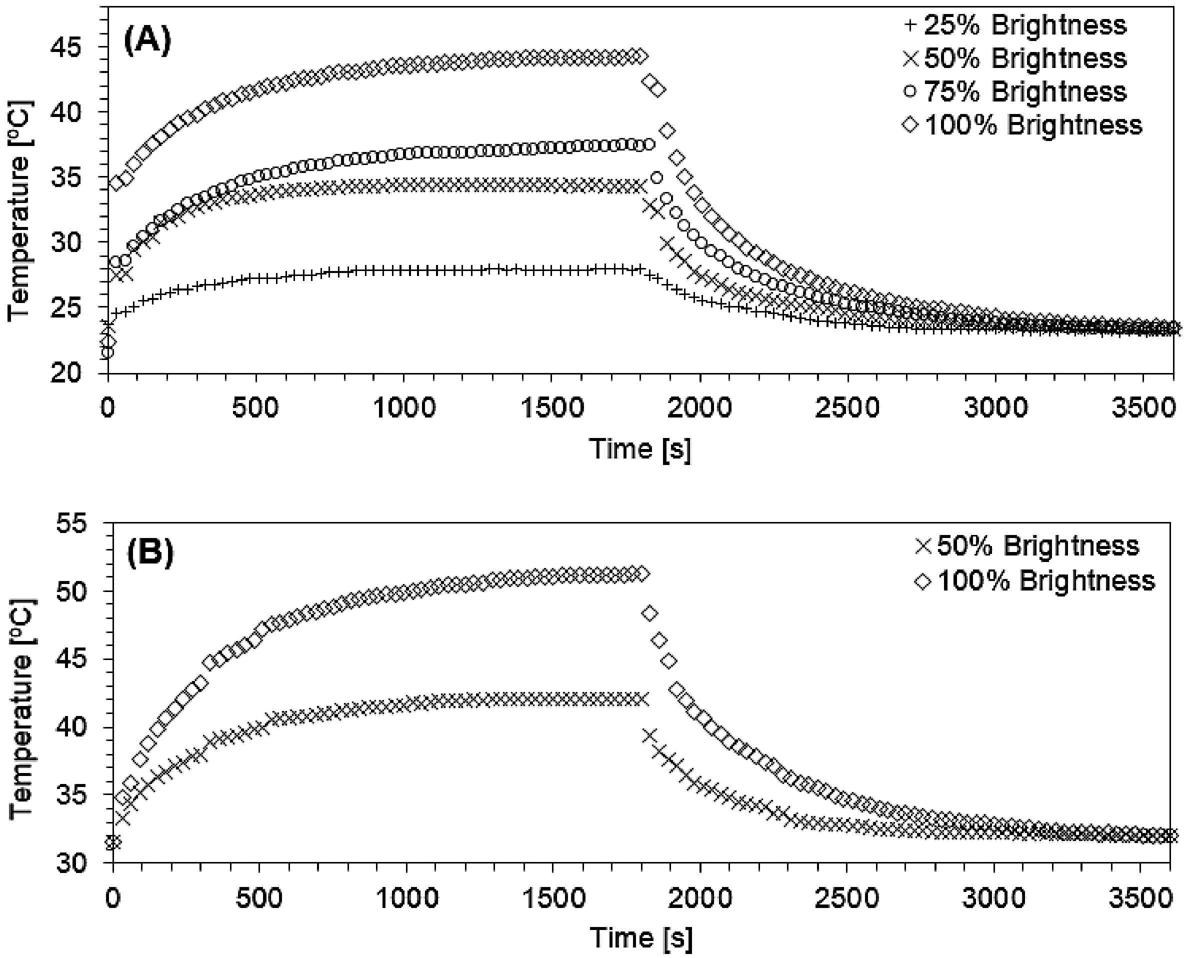

Figure 20. Thermal profiles of the LED light unit, 30 minutes after switching on and 30 minutes after switching them back off. (A) results from the first experiment at 22oC ambient conditions (B) results from the second experiment at 32oC ambient temperature

Table 3 Summary of the results from thermal profile characterisation tests

Ambient Temperature	**LED chassis ultimate temperature gain after switching on. [ºC]**		**Duration to gain 90% of the heat [min], after switching the LED on.**		**Duration to lose 90% of the heat [min], after switching the LED off.**	
	50% brightness	*100% brightness*	*50% brightness*	*100% brightness*	*50% brightness*	*100% brightness*
22 [ºC]	10.8	21.9	6.67	9.50	11.50	13.33
32 [ºC]	10.4	19.7	11.67	13.50	12.83	15.00

From these results, it can be concluded that it takes a longer time for the LED to cool down from the peak temperature after turning them off than it would reach the peak temperature after turning the lights on. However, in both cases, the amount of time to reach the steady-state was below 30 minutes. Since the time-frame for the transient state is small, and due to the much larger timescale of the internal humidity modelling aimed for this project, the transient state can be neglected, and therefore, only the terminal temperatures can be used for calculation of relative humidity inside the LED units.

(B) Steady-state terminal temperature modelling

An experiment was performed in the controlled environment chamber to study the maximum temperature that the air within the LED chassis reaches, in a wide range of ambient temperatures. The environmental chamber was programmed to cover an ambient temperature range of -25^{o}C to 50^{o}C and the LED was switched onto full brightness. The climate profile of this environmental chamber testing (GVA-03) can be found in the previous section of the report (Fig. 17).

Fig. 21 plots the LED's internal temperature against the ambient temperature of the controlled environment chamber. Based on these results an equation was obtained that can approximate the LED's operative internal temperature as a function of the ambient temperature. This equation was later used in the code to calculate the internal relative humidity of the LED units.

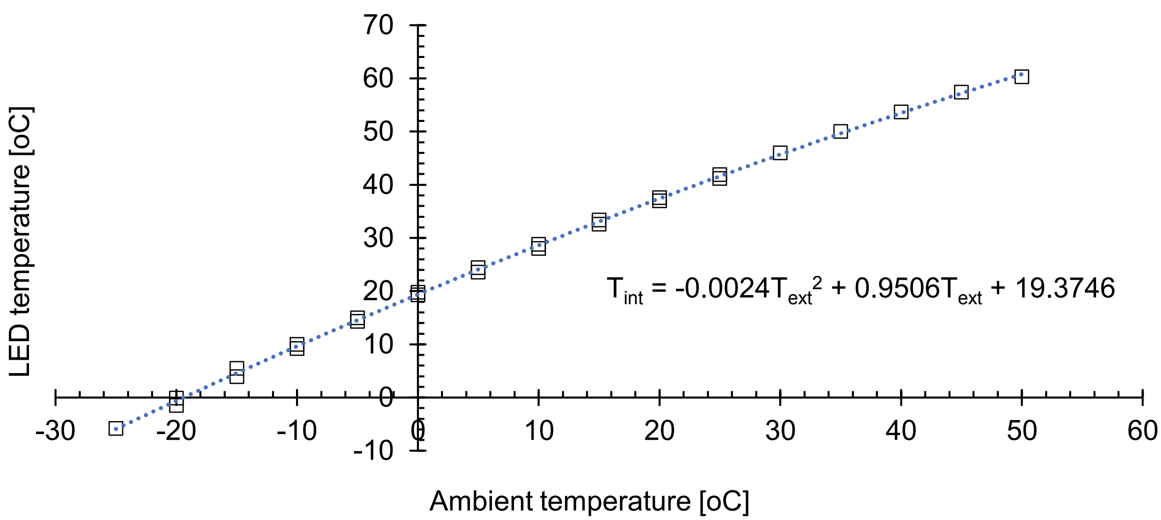

Figure 21. Final air temperature within the LED unit as a function of ambient temperature in full brightness mode.

Internal Humidity Modeling

The purpose of this project was to develop a model that can predict the relative humidity inside the LED housing for a given climate for an entire year. Moisture could enter or exit the LED housing through the Gore-Tex vent installed on the unit. Therefore, the amount of vapour that infiltrates and/or exfiltrates to/from the LED unit can be approximated through the theory of mass permeation. Experiments that were performed to characterise the vapour permeability behaviour of the Gore-Vent, helped with building a model that could predict the flow rate of the permeating vapour at a given climate.

Based on the results obtained from the permeability experiments (Fig. 14), Eqn. 8 can be used to approximate the rate of change of the internal moisture concentration within the LED unit, as a function of the difference between the internal and ambient moisture concentrations.

$$\dot{C}v_{int} = 0.000376 \times e^{0.15293\,\Delta C} \qquad \text{Eqn. (8)}$$

For small time steps where the difference between the internal and external vapour concentrations does not vary significantly, the updated internal moisture concentration (at time $t_0 + \Delta t$) can be approximated using Eqn. 9. Since the moisture diffusion through these vents is extremely slow, a time step of one minute was considered a suitable interval that was therefore used for the computer model.

$$Cv_{int}(new) = Cv_{int}(old) + (0.000376 \times e^{0.15293\,\Delta C})\Delta t \qquad \text{Eqn. (9)}$$

To calculate the internal moisture concentration at the next timestep ($t_0 + 2\Delta t$), it's important to update the concentration difference term (ΔC), using the Eqn. 10. The new external vapour concentration can be derived from the climate data file, while the new internal vapour concentration was computed from Eqn. 9.

$$\Delta C(new) = Cv_{ext}(new) - Cv_{int}(new) \qquad \text{Eqn. (10)}$$

After calculation of the internal humidity concentration at a given time, and by knowing the temperature, relative humidity can be determined using the psychrometric chart (or psychrometric function in computer programming). An algorithm that is used to model the internal relative humidity of the LED housing is described here.

(i) Obtain the ambient temperature and relative humidity for hour #**n** from the climate data file

(ii) Convert the ambient temperature and relative humidity for hour #**n** into "humidity concentration", using a psychrometric function.

(iii) For the first hour, assume the LED's internal humidity concentration is equal to the ambient humidity concentration (equilibrium).

(iv) Based on the internal, and ambient humidity concentrations, subtract to find the difference in humidity concentration (ΔC).

(v) If ΔC is not zero, calculate the new internal humidity concentration, using Eqn. 9, and assign the updated value to Cv_{int}.

(vi) Check the LEDs operational status for hour #**n** as per the prescribed schedule.

(vii) If the LED is off, assign the ambient temperature as the LED temperature at hour #**n**.

(viii) If the LED is scheduled to be on at hour #**n**, estimate the internal temperature from the correlation in Fig. 21.

(ix) Based on the LED's internal temperature and updated humidity concentration (Cv_{int}), employ psychrometric function to estimate the internal relative humidity.

(x) If the relative humidity is greater than 90%, report an escalated risk of condensation

(xi) Go to hour #n+1 and repeat the procedure.

Software Implementation

A computer program was developed (using Python 3.7) to simulate the LED's internal relative humidity profile for a given climate data file and a user-specified daily operation schedule. The code utilizes an iterative approach to the internal humidity modelling technique described in the previous section.

Algorithm and Model Implementation Methodology

The algorithm that is introduced herein aims to model the relative humidity inside the LED housing based on the operative schedule and climate data file for every single hour throughout the year. This method starts from hour #1 of the year and continues forward until it reaches the last hour of the year, #8760.

Starting from hour #1, the ambient temperature and relative humidity are obtained from the climate data file and the vapour concentration is calculated using a psychrometric function. Afterwards, the internal vapour concentration is estimated based on the internal moisture concentration at the previous time step and the ambient moisture concentration using Eqn. 9. The only exception is at hour #1, where the ambient moisture concentration is assigned as the internal moisture concentration. After finding the internal vapour concentration, the internal temperature is estimated based on the ambient temperature and the LEDs operation status.

Having both the internal temperature and vapour concentration, the relative humidity inside the unit is simply calculated from a psychrometric function. At this stage, the relative humidity inside the unit is estimated at hour #1 and the program will apply the same procedure for the next hours of the year. As the code is performing the simulation, a ".xlsx" file with the format shown in Fig. 7 is generated and updated until it reaches row number 8760, which corresponds to the last hour of the year. Fig. 22 demonstrates the logical flow chart that was used for computer implementation of this model.

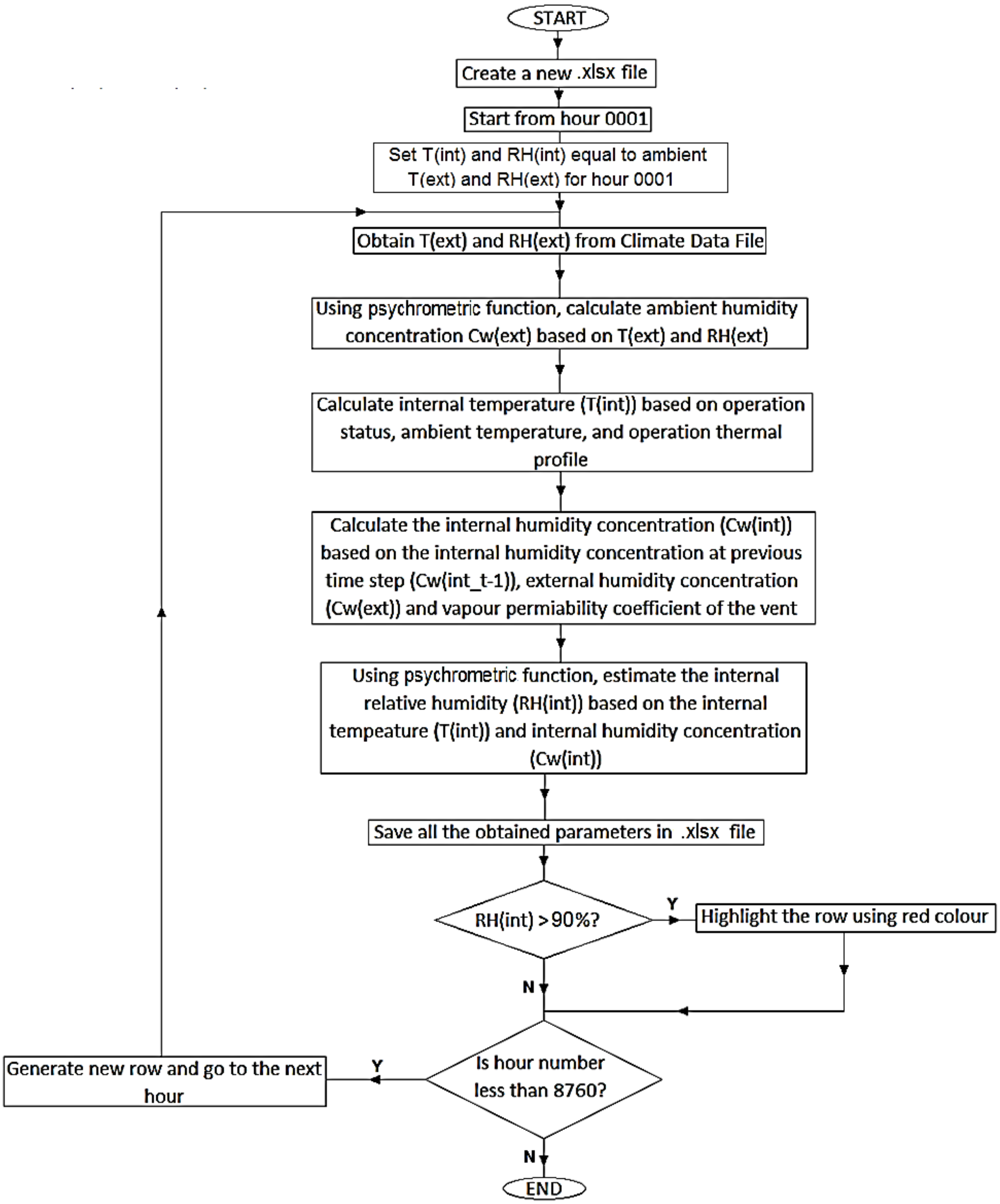

Figure 22. Logical flow chart for computational internal humidity modelling

Inputs and Outputs

To run the computer simulation, user inputs are required. User inputs for this computer program are the annual climate data file, Gore-Vent's active area, and the LED's switch-on and switch-off times. After running the code, an Excel file is generated that contains the forecasted internal relative humidity values for every hour of the year. The secondary output that will be displayed on the Python compiler is a list of hours that convey a higher risk of internal condensation (RH > 90%).

Validation and Error Analysis

All models require verification to be considered valid. To evaluate the accuracy of the developed computer model, sample simulations were run to compare the model results against experimental data. The hourly chamber (ambient) conditions for the GVA-02 and GVA-04 environmental experiments were filled in an excel file to represent the climate data file. The Moisture-X program was then run, and the simulation results for internal relative humidity were compared against the actual internal relative humidity obtained from experiments.

Fig. 23 demonstrates the trend of the internal relative humidity observed during the GVA-02 experiment and compares it to the results generated from the computer simulation. It can be seen that the modelled relative humidity trend is very similar to the actual trend. The average divergence from the experimental results was found to be 5.7%. The error was calculated as 2.2% when the LED is not in operation and 16.8% when the LED is in powered on.

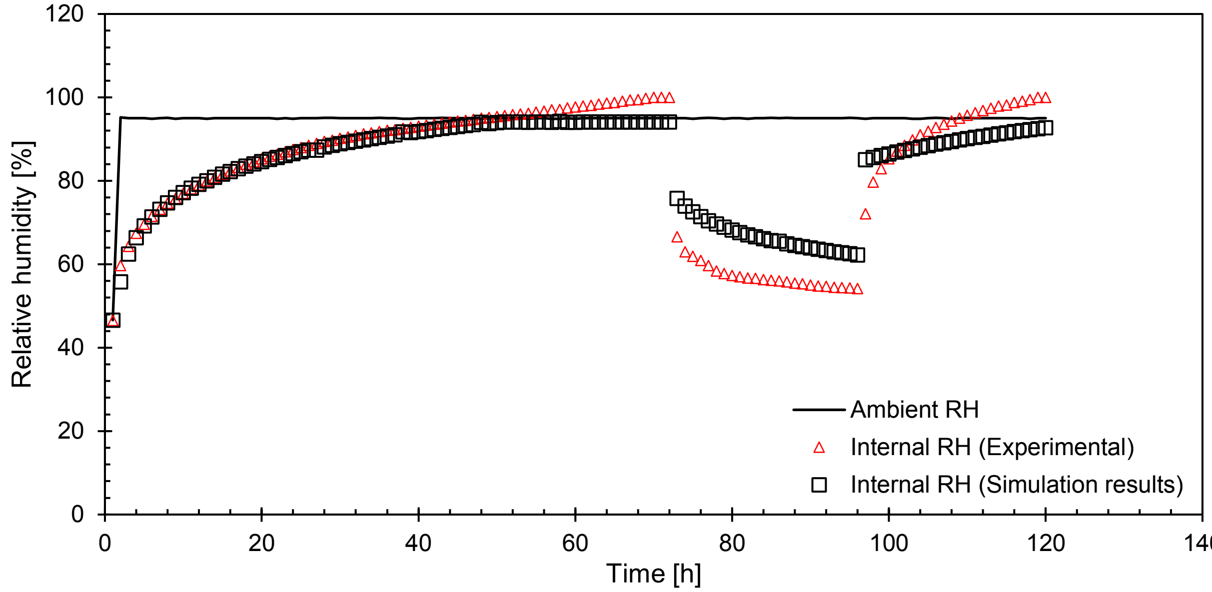

Figure 23. Experimental internal RH vs. modelled internal RH for GVA-02 testing

A similar approach was applied to the GVA-04 testing, in which the LED was exposed to a complex climate profile. Fig. 24 represents the trend of the internal relative humidity observed during the experiment and compares it to the results obtained from the computer simulation. The average divergence from the experimental results was found to be 19.4%. The error was calculated as 18.3% when the LED is not in operation and 22.3% when the LED is powered on.

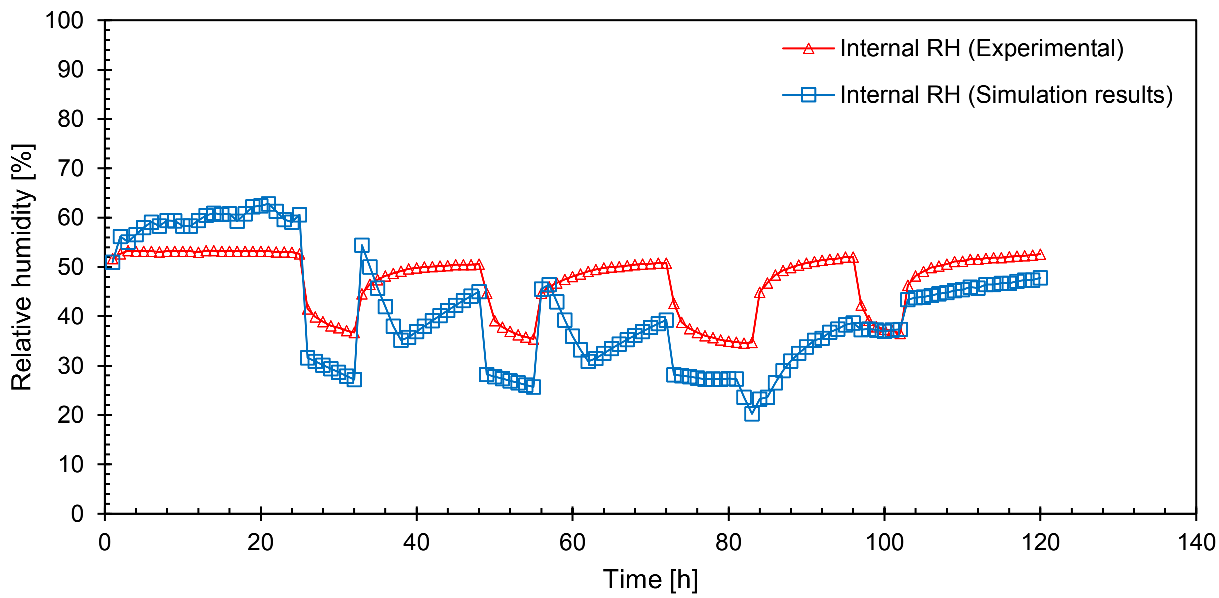

Figure 24. Experimental internal RH vs. modelled internal RH for GVA-04 testing

From both comparisons above (Figs. 23 and 24), it can be noted that the average simulation error is higher when the LED is in operation. The reason for this behaviour may possibly be due to the presence of a temperature gradient within the air inside the LED housing. The air closer to the LED array and the printed circuit board is expected to have a higher temperature than the air closer to the surrounding walls due to its proximity to the heating source. Therefore, the on-board temperature and humidity sensors in the LED unit records a higher temperature than the actual average air temperature within the chamber. These higher-than-actual temperature readings are used in the code in order to calculate the internal air temperature which is later used to calculate the relative humidity. Another contributing factor to the increased error might be the transient gain of temperature within the LED chamber. Air near the sensors close to the PCB board may reach the steady-state maximum temperature in a shorter timeframe, than the air farther from the heating source, and closer to the walls.

Additionally, the simulation error can be linked to the complex moisture diffusive behaviour of the Gore-Text vents. As observed in Fig. 10, the moisture passage rate through these vents may change significantly as a result of prolonged exposure to moist environments. High humidity environments may possibly contribute to microscopic scale droplet formation within the vent's fibre structure which can result in a partial clogging. A microscopic view of the Gore-Tex vent is shown in Fig. 25. It can be seen than the vent is comprised of a complex multi-layer fabric structure, with a very fine, densely packed rectangular mesh laying underneath a larger randomly packed fibre structure.

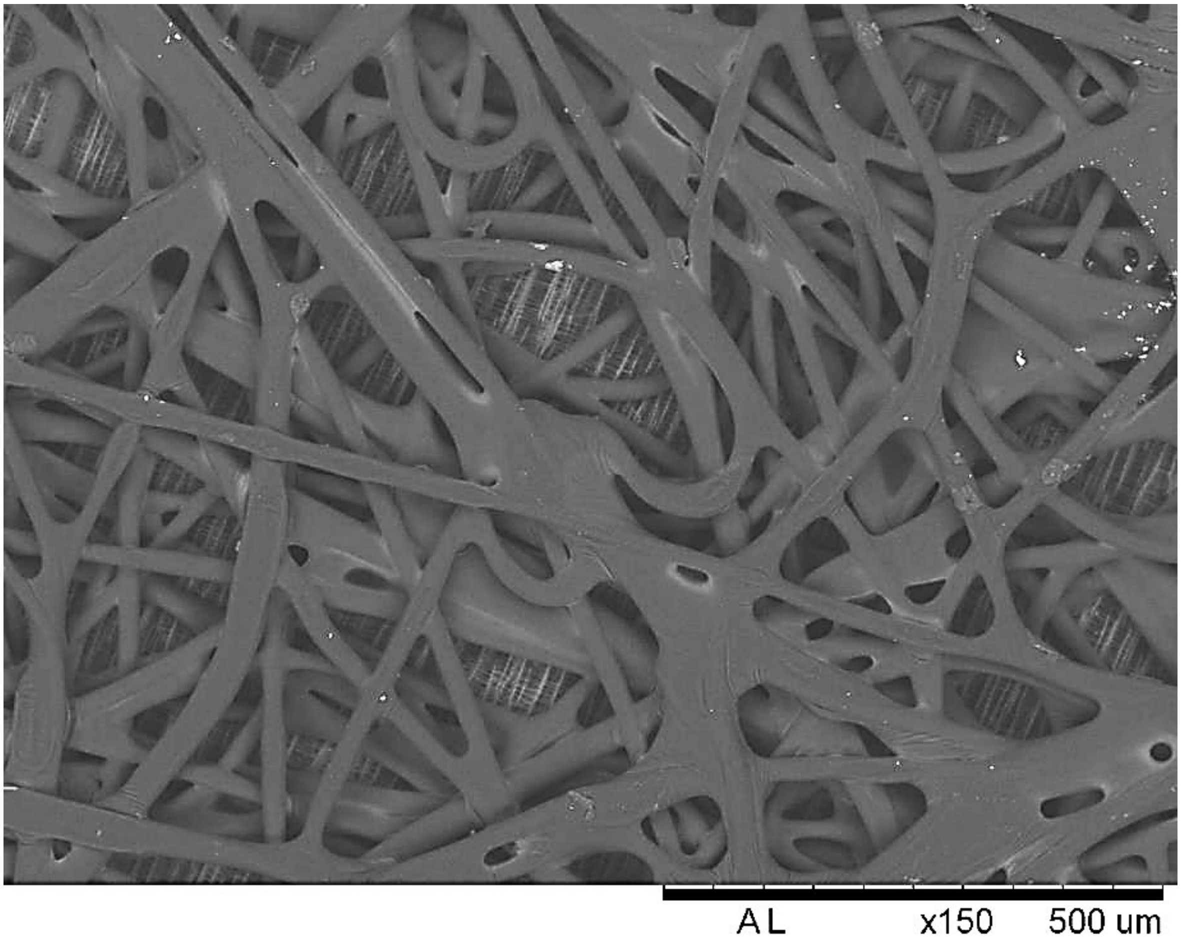

Figure 25. A magnified view (x150) of the Gore-Tex vent.

Conclusions and Discussions

A numerical model was developed to calculate the internal relative humidity conditions of a vented GVA LED unit using the climate data, vent size and operation schedule of the lights. The model uses the principles of mass permeation through a medium and calculates the rate of moisture transfer through the vent based on the internal and external humidity concentrations. To determine the internal vapour concentration of the LED enclosure one must know the internal relative humidity and temperature. First, the permeability of the vent was characterized at the University of Toronto and improved during the environmental chamber testing at GVA. Next, the thermal profile of the LED was characterized to determine an accurate correlation for the internal chamber temperature during LED operation for various ambient conditions.

Using this data and the climate data file, one can calculate the internal moisture concentration for every hour of the year. All humidity concentration values are then converted into relative humidity and an excel file is generated. The output Excel file contains the internal relative humidity and temperature predictions for all the hours in a year. After performing a simulation, a list of hours is displayed by the compiler that conveys an elevated risk of internal condensation. The model was then validated by comparing the experimental data with that predicted by the model. A good correlation of the model and the experimental data was noted. An average divergence from the experimental results was found to be 19.4%. The error was calculated as 18.3% when the LED is not in operation and 22.3% when the LED is powered on for the internal relative humidity conditions.

The model assumes that the vent is clean and the surrounding ambient air is stagnant. Over the lifecycle of the LED unit, the vent may become clogged or contaminated which reduces the vapour permeability coefficient of these vents. This reduces the model accuracy. The error is also expected to increase with the presence of significant inbound wind, which can lead to a convective mass transfer of moisture and cooling of the LED unit.

The software is computationally efficient and can be adapted to different vents or LED units by conducting a similar methodology outlined in this report.

Recommendations

Several steps can be taken to minimize the risk of condensation in the LED chassis. Some steps can be made during the manufacturing process, and other steps can be made during and after installation to mitigate the risk of internal condensation. Recommendations are outlined in Table 4.

Table 4. Recommended actions to reduce the chance of internal condensation

Process Stage	Recommendation(s)
Manufacturing	Using larger vents can facilitate the flow rate of moisture into and out of the unit. It's recommended to use the smaller vents for arid or semi-arid climate when the relative humidity is normally below 60%. In these types of climate, temperature fluctuations pose a greater risk of concentration than the ambient humidity conditions. Risk of condensation overnight is greater and since the moisture concentration changes are very slow in smaller Gore-Tex vents, the internal relative humidity can rapidly rise once the temperature falls overnight. This recommendation is only applied to arid and semi-arid climate and can lead to adverse effects if used in a tropical or moist climate where the relative humidity is normally above 60%.
Shipping, Handling and Installation	Avoid contamination during installations, shipping and installation process
Operation	Slow dimming is highly recommended to prevent rapid temperature loss within the LED enclosure, which in turn results in a rapid increase in the relative humidity.
	Utilization of the Moisture-X software to determine the high-risk hours for a specific location, and leave the LEDs on during those hours, where the internal relative humidity is expected to surpass 90%.
	A recommendation is to use a control system that constantly collects, monitors and processes the temperature and relative humidity data for the ambient environment at an installation. The control loop can be used to predict in real-time cases when turning off the LEDs might cause condensation.
Maintenance	The vents are expected to experience partial/full blockage after prolonged exposure to dust and other air pollutants.

References

[1] Cussler, E. L. (1997). *Diffusion: Mass transfer in fluid systems*. New York: Cambridge University Press.

[2] American Society of Heating, Refrigerating and Air-Conditioning Engineers (1997). *ASHRAE Fundamentals Handbook*

[3] Hamilton, A. G. (1982). Numbers, sets, and axioms: the apparatus of mathematics. Cambridge University Press. p. 83. ISBN 978-0-521-24509-8.

[4] Draper, B. (2016). *Python programming: A complete guide for beginners to master Python programming language*. United States of America

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