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Mechanism of Heat and Mass Transfer in Sandwiched Fibrous Insulations Subjected to Moisture Absorption and Condensation

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Abstract

This paper presents experimental and theoretical modeling investigation of heat and moisture transfer within Glass fibre reinforced polymer composite (GFRP) Laminates subjected to variable environmental conditions. Under various circumstances, moisture can appear in the insulation matrix. Since the temperature at the boundary changes dynamically with meteorological conditions, heat and mass transfer and moisture between boundaries can appear in this case. A transient model of the heat and mass transfer, including the sorption and condensation processes was studied. The paper includes a numerical model considering the dynamical changing of the boundary temperatures. A parametric study considering different amplitudes of temperature change, different moisture masses and different thicknesses of the insulation matrix was made. The accumulation and distribution of water content is a combined result of moisture absorption, condensation and liquid water movement. It was found that a relatively small mass of water in the insulation matrix can result in a significantly increased average heat flux during a periodic cycle. The numerical results were compared with experiments and found in good agreement with the numeric.

1. Introduction

Heat and moisture transfer in porous media with phase change is important to a wide range of scientific and engineering fields [1,2] such as civil engineering, energy storage and conservation, as well as functional clothing design [3], etc. Because of presence of some cracks and flaws in these facings (fabrics), the untight junctions between them and the inappropriate storage, moisture can appear in insulation matrix. Furthermore, because of the fabrics' high tightness, the drying is usually not possible. The presence of this moisture can result in a physical and chemical deterioration of the insulation matrix and thin coverings, which reduces the life time of the insulation system. In addition, the insulating properties of whole system tend to deteriorate.

Jintu fan et al. [5] considered a model of coupled heat and moisture transfer with phase change and mobile condensates in fibrous insulation and concluded that the moisture movement within the batting was induced by the pressure gradient. Kyunghoon Min et al. [6] used a mathematical model to simulate the heat and moisture transfer from skin to environment through fabrics by including the radiation heat transfer between surfaces and the surface diffusion along fibers. The result shows that the contributions of radiation and conduction through air are approximately 20% each of the total heat flux. Huijun Wu, Jintu Fan [7] evaluated the effect of positions of different types of battings on the moisture accumulation and thermal insulation performance of the clothing assemblies. They found that placing the hygroscopic wool batting in the inner region (i.e. closer to the body) and the non-hygroscopic polyester batting in the outer region (i.e. away from the body) could reduce the moisture accumulation within and the total heat loss through clothing assemblies. S. Veiseh et al. [8] determined the conductivity of three kinds of mineral wools (glass wool, rock wool, and slag wool) by using reference curve concept. This concept was also used to evaluate the thickness and mean temperature's effects on fibrous insulation matrix by using different models. R. Arambakam et al. [9] found that heat conduction through the solid fibrous structure increases by increasing the material's

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solid volume fraction, fiber diameter, and fibers' through-plane orientations. The in-plane orientation of the fibers, on the other hand, did not show any significant influence on the material's conductivity. It was also shown that the microstructural parameters of fibrous insulations have negligible influence on the material's performance if the conductivity of the solid phase is close to that of the interstitial fluid.

Developing their own model, Motakef and El-Masri [10] and Shapiro and Motakef [11] studied condensate accumulation and its movement inside the thermal insulation. A major discrepancy in the temperature profile for their modeling and measurements occurred in the condensation zone. Wijeysundera et al. [12] later upgraded the study by developing a non-stationary numerical model for a determination of the condensate accumulation in the specimen. The model corresponds well with the measured data for the first 70 h of the coupled heat and mass transfer process. Thomas et al. [13] monitored the temperature change and moisture migration in an initially wet glass–fiber insulation slab with impermeable boundaries subjected to one-dimensional temperature gradients on a guarded hot plate.

In previous researches we found that in most of the cases, while considering a local moisture source, after a number of periodic cycles the moisture spreads approximately equal all over the fibrous insulation matrix. Because of that we can assume, the mass transfer can be studied one dimensionally.

2. Problem Formulation

The model was developed by considering one-dimensional with coupled heat and mass transfer in fibrous thermal insulation with impermeable boundaries. And hence for an arbitrary changing of boundary temperatures, the calculation for heat and moisture transfer as well as the fields related to temperature and moisture concentration can be done easily. In the present work, the coupled heat and moisture transfer through fibrous insulations of GFRP was also investigated by an experiment using some tests. For developing the model the following assumptions were taken into account.

1. The insulation matrix is homogenous.
2. A local thermal equilibrium exists between the solid, liquid and gas phases.
3. Convection is negligible in the insulation matrix.
4. The liquid phase is immobile.
5. The total gas-phase pressure in the insulation matrix is constant.
6. A local thermal equilibrium exists between the solid, liquid and gas phases and a local moisture equilibrium exists between the sorbed moisture at the surface of fibers and the moisture content of the air and between liquid water and the moisture content of the air.

The following equations are used for modeling of Heat and mass transfer and solved by using Crank-Nicholson implicit method.

Since radiation will not affect much at low temperature and as per assumption no. 3 hence energy equation can be written as:

Energy equation:

$$\frac{\partial}{\partial x}\left(k_e \cdot \frac{\partial T}{\partial x}\right) - \dot{q} = \rho_e \cdot c_{p,e} \cdot \frac{\partial T}{\partial t} \quad \ldots.\{1\}$$

Water-Vapor diffusion equation:

$$\frac{\partial}{\partial x}\left(D_e \cdot \frac{\partial C}{\partial x}\right) + \Gamma = \frac{\partial \epsilon_g C}{\partial t} \quad \ldots.\{2\}$$

Where Γ is the rate of sorption/desorption, condensation/evaporation (kg/m^3s) can be determined by summing the terms as rate of moisture uptake and release during sorption/desorption and the evaporation/condensation process. And hence can be written as:

$$\Gamma = \Gamma_{so} + \Gamma_{fg}. \quad \ldots.\{3\}$$

Where

$$\Gamma_{so} = -\frac{\partial C_{so}}{\partial t} = -\frac{\partial u}{\partial t} \cdot \rho_f \quad \ldots.\{4\}$$

is the rate of sorption/desorption which can be related to mass of sorbed moisture (u).

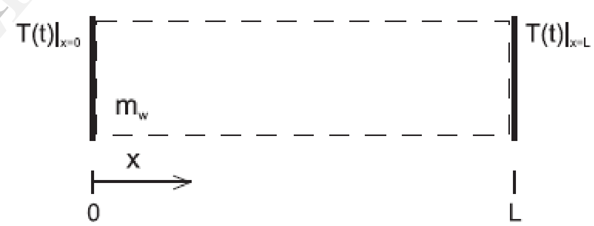

Figure 1. Schematic diagram of insulation matrix.

And

$$\Gamma_{fg} = -\frac{\partial C_1}{\partial t} \quad \ldots.\{5\}$$

is the rate of conservation of liquid phase.

Local values of the thermal conductivity of the insulation matrix change significantly with the liquid content and can be determined using following equation

$$k_e = \varepsilon_s \cdot k_s + \varepsilon_1 \cdot k_1 + \frac{\varepsilon_g \cdot (\rho_a \cdot k_a + \rho_v \cdot k_v)}{\rho_a + \rho_v} \quad \ldots.\{6\}$$

For the same case the specific heat capacity can be determined as:

$$c_{p,e} = \frac{(\varepsilon_s \cdot (\rho \cdot c_p)_s + \varepsilon_1 \cdot (\rho \cdot c_p)_1 + \varepsilon_g \cdot ((\rho \cdot c_p(\rho \cdot c_p)_p))}{\rho_e} \quad \ldots.\{7\}$$

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and the density

$$\rho_e = \varepsilon_s \cdot \rho_s + \varepsilon_1 \cdot \rho_1 + \varepsilon_g \cdot \rho_g \quad ....\{8\}$$

The diffusion coefficient of the water vapor in the insulation matrix is assumed to be a function of the temperature, the turtousity of the insulation matrix and the volume fraction of the gaseous phase. It can be determined by:

$$D_e = \frac{\varepsilon_g}{\tau} \cdot D_{12} \quad ....\{9\}$$

Since total volume is always constant. Hence expression for different volume fractions refers to:

$$\varepsilon_s + \varepsilon_1 + \varepsilon_g = 1 \quad ....\{10\}$$

The rate of heat generation ($\dot{q}$) in equation {1} can be determined by summing of the heat source/sinks, appearing during sorption/desorption and condensation/evaporation process.

$$\dot{q} = \Gamma_{so} \cdot h_{so} + \Gamma_{fg} \cdot h_{fg} \quad ....\{11\}$$

The relative humidity (ϕ) can be expressed as:

$$\phi = C/C_s \quad ....\{12\}$$

The term C_s can be determined by using saturation-pressure equation[24] and by considering the ideal gas law into consideration.

$$C_s = \frac{610.8}{R \cdot T} \cdot \exp\left(\frac{17.08085 \cdot T}{234.175 + T}\right) \quad ....\{13\}$$

The binary diffusion coefficient of water vapor used in equation (6) can be determined by using the following relation[24].

$$D_{12}(T) = 23.4 \cdot 10^{-6} \cdot \left(\frac{T + 273}{273}\right)^{2.3}. \quad ....\{14\}$$

2.1 Boundary conditions

The temperatures at the boundaries changes with meteorological parameters and with the temperature of the indoor environment and hence can be expressed as:

$$T|_{x=0} = T_0(t) \quad ....\{15\}$$

$$T|_{x=L} = T_L(t) \quad ....\{16\}$$

For Moisture transfer, since insulation matrix boundaries are impermeable to moisture. Hence

$$-D_e(T)\left(\frac{\partial C}{\partial x}\right)_{x=0} = 0 \quad ....\{17\}$$

$$-D_e(T)\left(\frac{\partial C}{\partial x}\right)_{x=L} = 0 \quad ....\{18\}$$

2.2 Solution procedure

Equation {1} and {2} were discretized using Crank-Nicholsan Method for numerical calculation. Numerical code was written in the numerical simulation environment Matlab. The tri-diagonal system of equations obtained by the discretization was solved using the TDMA algorithm [25].

Firstly we begins with a determination of the first iteration of the temperature field (Eq. (1)). The sorption/desorption (Γ_{so}) and condensation/evaporation (Γ_{fg}) rates are determined next by iterating the vapor diffusion equation (Eq. (2)). The process was repeated untill upto the convergence criteria is reached, after then the next variation of the temperature field (Eq. (1)) is determined, using updated values of Γ_{so}, Γ_{fg}. The temperature-dependent parameters (D_{12} – Eq. (14), C_s – Eq. (13)) and the liquid-content-dependent parameters (De – Eq. (9), ke – Eq. (6), $c_{p,e}$ – Eq. (7), and density – Eq. (8)) were updated during every iteration. The iteration procedure continues until the residuum of the temperature and the concentration fields are less than 10^{-4} and 10^{-7}, respectively. After that the next time step calculation starts.

3. Experiment:

Following tests were included in experiment.

3.1 Measurement of moisture absorption

For measuring moisture absorption, condensation and other properties, the following steps were used while performing the experiment:

[1]. A number of samples of GFRP laminated glass were taken of some specific dimensions.
[2]. The top and bottom layer of the specimen were condition at an air conditioned room with temperature at 25.0 ± 0.5^{0}C and humidity at 65 ± 5% for at least 24 h.
[3]. Weigh and record the weights of each sample.
[4]. All Samples were exposed to temperature controlled water containers.
[5]. The samples were kept in water for different time durations such as 3 days, 6 days, up to 18 days etc.
[6]. After a pre-set time (i.e., 3, 6, 9, 12, 15 or 18 days), take out each sample and weigh them immediately using an electronic balance.
[7]. Calculate the percentage of moisture or water accumulation due to absorption or condensation on each sample by

$$Wc_i = \frac{W_{ai} - W_{oi}}{W_{oi}} \times 100\% \quad ....\{19\}$$

where, W_{ai} is the weight of the ith sample after test for a pre-set period of time, W_{oi} is the weight of the ith sample before testing, and Wc_i is the increase in water content in percentage.

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Table 1 : specimens exposed to water

Sample no.	Weight of sample with exposure time (in grams)						
	0 days	3 days	6 days	9 days	12 days	15 days	18 days
1.	17.7	18.4	19.2	19.6	19.8	19.9	20.2
2.	18.9	20.5	21.6	22.1	22.4	22.6	22.8
3.	19.0	19.8	20.8	21.9	22.2	22.4	22.6
4.	19.4	20.2	20.8	21.3	21.9	22.2	22.4
5.	19.6	20.6	21.2	21.6	22.0	22.4	22.5
Total weight	93.6	99.5	103.6	106.5	108.3	109.5	110.5
% of weight gain	0	6.3034	10.6837	13.782	15.7051	16.9871	18.0555
Rate of absorption	0	1.9666	0.6833	0.3222	0.15	0.08	0.0555
Change in tensile modulus	0.97	0.964	0.952	0.945	0.924	0.913	0.902

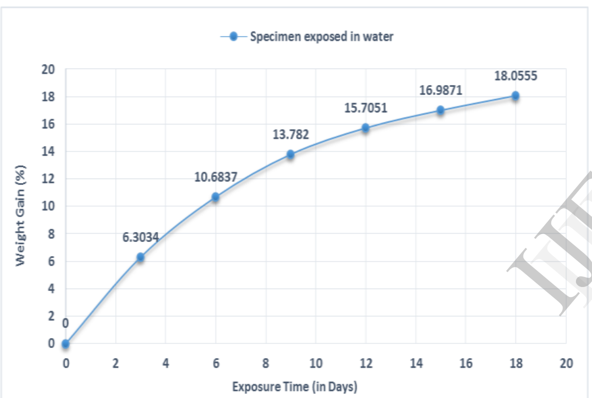

Figure 2. Weight gain vs Exposure time for Specimen exposed in water

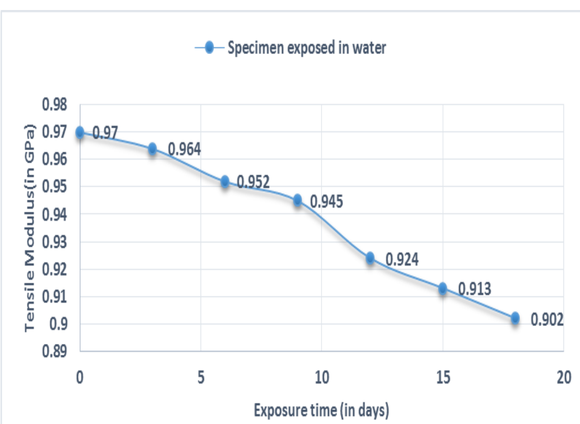

Figure 3. Tensile Modulus vs Exposure time for Specimen exposed in water

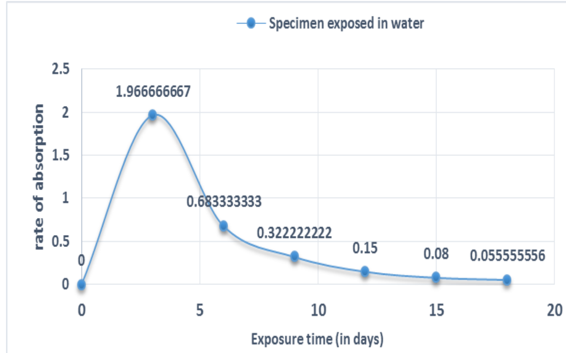

Figure 4. Rate of absorption vs Exposure time for Specimen exposed in water

3.2 Mechanical Characterization test:

Laminated glass interlayer plays a mechanical rule, both at rupture and in the serviceability domain, it is important to evaluate the consequences of weathering on the mechanical properties of interlayer polymer. For investigating the damage of poly (vinyl butyral) laminated glass under weathering action, specimens were subjected to laboratory degradation by moisture, UV radiation and thermic cycles.

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3.2.1 Accelerated Moisture Action

Specimens consisting of two composite glass laminated with PVB interlayer with thickness 8-1.52-8 mm and thickness 8-0.76-8 mm respectively with diameter 23.06 mm were taken. Some of them were intended for environmental damage. Particularly, some specimens were subjected to moisture action keeping them suspended over a covered thermostatic bath at the temperature of 50° (about 100% R.H.). Accelerated moisture damage can hardly be compared to some environmental conditions; at the moment our aim is to measure the consequences of extreme moisture action rather than try to reproduce a specific field situation.

As a consequence of moisture diffusion, laminated glass began to exhibit opacity from the boundary towards the center of the button. After 33 days (about 809 hours) specimens were opaque for some millimeters; specimen with 8-1.52-8 mm was conditioned at room temperature and humidity, till it recovered the original transparency, and then tested. Other 12 specimens, six of them 8-0.76-8 mm and six of them 8-1.52-8 mm, were subjected to moisture action with the same procedure for about 226 days (5425 hours). At the end they were completely opaque, so that the complete transparency recovery took about six months. Three of the six specimens 8-0.76-8 mm were also affected by delamination, from the boundary towards the center.

4. Results & Discussions

The aim of this work is to investigate the absorption of moisture in different glass composites under different moist environmental conditions to understand the overall effect of moisture absorption on the weight and mechanical property. The experimental results are presented in table 1.

4.1 Effect of moisture absorption on weight and tensile property

The way of moisture absorbed is dependent upon many factors like type of climatic exposure, severity of exposure, humidity and temperature. The analysis of results is done by plotting the curve of weight gain verses exposure time and tensile modulus verses exposer time as shown in graph 1 and 2. Hence investigation of the effect of moisture impact on GFRP composite laminates under different moisture environmental conditions were done. It can be easily observed that while in start, there is almost a linear increase in the equilibrium moisture content, then after gradually increases and expected to approaches constant saturation level. In the graph 2, it was observed that tensile modulus decreased to some extent with the presence of moisture. Fibre strength was also negatively affected, possibly due to either leaching out of the glass fibres interface layer or glass fibre embrittlement, less effective bonding and load distribution at the fibre–matrix interface.

4.2 Effect of water on tensile modulus

The tensile strength of GFRP laminates exposed to water at room temperature is decreases gradually over exposure period of 18 days after continuous exposure the reduction of tensile modulus expected to maintain constant. The reasons can be initially rapid entering of water particles into fibre- matrix interface due to capillary action. After certain period of time, a saturation stage is reached and no more water seep into fibre matrix phase. All the voids of laminates filled with moisture and which act as a plasticizer to fevor the property.

5. Conclusions

The experimental results shows weight gain and reduction in tensile modulus of GFRP Specimens in water. The GFRP Composites were experimental investigated and found the remarkable reduction in weight as the effect of moisture absorption. The mechanical strength (tensile modulus) of GFRP Composites were also found in effective decreased values which are exposed to water and at room temperature for different exposure time.

Due to presence of moisture in matrix of composite material causes following factors:

i. Swelling of matrix,
ii. Debonding of inter-phase,
iii. physical damage of matrix inter-phase and
iv. hydrolysis of composite materials

these all factors are also the main reasons for the reduction in tensile strength.

The following conclusions may be drawn for this study:

i. The Composite material moisture absorption is more.
ii. The presence of moisture or water particles in the matrix, fiber-matrix interface of composite materials attack on the glass fibres, all these are the reason for the reduction of mechanical properties. But in both normal and frozen conditions the damage is more severe in case of frozen moisture.

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