Abstract

Literature review suggests that building energy consumption is dependent on climatic conditions and hygrothermal characteristics of building materials. This paper summarises the impact of hygrothermal characteristics of building materials on energy consumption in context of five climate zones of India. Numerical simulations of a test building were conducted with and without consideration of moisture transfer through/at walls. EnergyPlus (2016) software was employed for hygrothermal analysis. Moisture absorption at the inner wall surfaces reduces indoor relative humidity. This reduces the heating energy requirement by around 20% for temperate, composite and cold climates. The cooling energy requirement increases in all climate zones but the relative increase is less than 2%.

Introduction

Moisture transfer through the building envelope causes structural damage and changes its thermal characteristics. The coupled heat and mass transfer phenomena across the envelope is highly dependent on the hygrothermal characteristics of building material. Material properties such as porosity and permeance of water in vapour and liquid forms dominates moisture migration through/around the building envelope. Hygrothermal simulations play an important role in predicting the moisture movement through the building envelope and therefore the energy transfer associated with it. Numerous authors have reported the effect of heat and moisture transport on energy consumption of buildings. Consideration of the hygroscopic interaction of spruce walls by Gaur and Bansal (2002) showed that the room temperature could be altered by 2 to 3 °C. Cooling of indoor air due to moisture transfer was observed by Liu et al. (2013). This would, in turn, affect the air-conditioning energy requirement. Osanyintola and Simonson (2006) estimated the effect of hygroscopic materials on energy consumption in buildings. They observed that the heating and cooling energy consumption can be reduced by 5% and 30 % respectively by employing a controlled HVAC system. Qin et al. (2011) predicted overestimation of energy costs for hot and humid climates when hygrothermal effects were not modelled. This would result in oversizing of air-conditioning plant and therefore its inefficient operation. Hygrothermal simulations with a calibrated model were carried out by Moon et al. (2014). Reduction in the amplitude of fluctuations in relative humidity was observed. The study suggested that the heating and cooling energy can be underestimated without the consideration of moisture transfer in buildings. A method based on simple measurements for assessing the moisture buffering ability of indoor surfaces and interior objects was presented by Janssen and Roels (2009). Tran Le et al. (2016) observed that moisture buffering capacity of building envelope and indoor objects can reduce the energy required for heating. Thus, previous studies suggest that moisture buffering has a direct relation with energy required for air-conditioning.

Several materials have been explored by researchers to exploit moisture buffering property of different materials. The behaviour of bio-based material like hemp concrete was studied by Tran Le et al. (2010). Huang et al. (2018) assessed the hygrothermal performance of natural bamboo fibre. Liu et al. (2017) studied the buffering capabilities of diatomite and gypsum boards and Kang et al. (2018) evaluated the hygrothermal behaviour of gypsum boards by adding porous materials. Woloszyn et al. (2009a) studied the effect of combining relative humidity sensitive ventilation and moisture buffering capacity of materials on the energy efficiency in buildings. Maalouf et al (2015) assessed the hygrothermal behaviour of hemp-starch composites and studied its impact on energy consumption and indoor comfort. They found that relative humidity sensitive ventilation reduces the energy consumption by 11.8 %. Labat and Woloszyn (2016) carried out experimental and numerical studies on a wooden frame building vapour tight and vapour open walls. They found that yearly heating energy was not affected by relative humidity sensitive ventilation but smoothed the energy demand. Moisture transfer affecting the U-value of walls has been studied by many authors. Fengolio et al. (2018) assessed hygrothermal performance of perlite based thermal insulating plaster for energy retrofitting of buildings. They observed reduced U-value of walls due to moisture transfer. Recently, Khoukhi (2018) showed that the conductivity of polystyrene insulation material varied significantly and resulted in 8 % increase in the cooling load with respect to the base case. Finally, the climate of a region determines the moisture response of building materials. Liu et al. (2015) investigated hygrothermal performance of residential buildings hot and cold zones China. For a test building with hygroscopic materials like gypsum and wood fibre, Zhang et al. (2017) observed a potential energy saving of 25-30 % for temperate and semi-arid climates. It is clear...
from the literature that moisture interaction in and around the building envelope plays an important role in predicting building energy consumption. The magnitude of this interaction is dependent on building materials, air change rate and climatic conditions.

India experiences a variety of climatic conditions across its territories. Also, there is a high humidity period during the monsoon season. Studies on hygrothermal simulations for air-conditioned buildings with typical materials and different climatic zones of India have not been reported in the literature. In India, buildings account for more than 20% of total energy use. The HVAC systems contribute to 31% of the energy used by commercial buildings in India. The total constructed area is expected to reach 10,400 million square meters in 2030 (Tanmay Tathagat et al. (2014)). Also, the energy consumption of residential sector in India is estimated to increase by eight times by 2050 (Rawal and Shukla (2014)). In this context, this work focusses on hygrothermal performance of an air-conditioned building across five climate zones of India.

Different models are available for predicting the heat and moisture transport of buildings. Künzel (1995) presented a comprehensive study of the combined heat and moisture transfer mechanisms. Different modelling approaches/programs for analyzing moisture transport in building envelope were reviewed by Woloszyn et al. (2009b). Tariku et al. (2010a) reported a one-dimensional coupled heat and moisture model for multi-layered porous media. Apart from the component specific moisture modelling techniques several whole building models have been reported in the literature. Kunzel et al. (2005) presented a combined heat and moisture transfer model which coupled the building envelope with interior space for predicting indoor temperature and relative humidity. The effect of hygrothermal simulations on whole building performance has been studied in reports by Qin et al. (2009) and Tariku et al. (2010b). EnergyPlus (2016) is a widely used whole building simulation software which is freely available. It has different models for simulating heat and moisture transfer in buildings. Models like conduction transfer function (CTF) and conduction finite-difference (HT) yield quick results. However, these models don’t consider heat and moisture transfer inside the building envelope. They also ignore the moisture absorption and desorption at wall surfaces. Nevertheless, these models estimate indoor relative humidity by conducting a moisture balance over the indoor volume. Moisture brought in from outdoor air (infiltration/ventilation) and indoor sources is considered in these models. As compared to the above models, combined heat and moisture (HAMT) model considers detailed moisture interaction through the building envelope. It also accounts for moisture transfer between the building walls and the surrounding environment. Finally, EMPD (effective moisture penetration depth) method is an intermediate level model which considers moisture penetration in the envelope but with some inaccuracies. Mahattanatawe and Charuchaimontri (2015) conducted thermal-only and hygrothermal simulations for a city hall in Thailand. They observed that the cooling energy consumption predicted by the hygrothermal model was 4-7% lower than the thermal-only model. Yang et al. (2015) evaluated different models in EnergyPlus (2016) for evaluating moisture effect on building energy consumption for three different climates. They concluded that HAMT model is an appropriate choice for simulating heat and moisture transport in and around the building envelope. In this work, hygrothermal simulations are carried out with both the HT and HAMT models. An attempt is made to quantify the differences in heating and cooling energy requirement between these models for cities in different climate zones of India. Effect of different wall constructions with typical building materials and air change rates is also studied in this paper.

**HAMT model verification**

The HAMT and HT models of EnergyPlus (2016) have been previously verified in the literature (Wood et al. (2013), Qin and Yang (2016)). However, basic verification of the HAMT model is carried out in this study to have confidence in the results obtained subsequently. The verification is carried out by simulating the analytical cases presented by Bednar and Hagentoft (2005). For these cases, the BESTEST building geometry (Judkoff and Neymark (1995)) is simulated. The building is a single zone rectangular shoe-box configuration with dimensions of 8m x 6m x 2.7m. The walls are made up of a monolithic layer (150 mm) of aerated concrete. There is a constant air change rate of 0.5 h⁻¹ with internal moisture generation of 500g/h from 09:00 h to 17:00 h. The outdoor air temperature and relative humidity are fixed to 20 °C and 30% respectively. Two different scenarios are considered: a) completely vapour tight interior and exterior surfaces; b) exterior surface completely vapour tight with moisture absorption/desorption at interior surfaces. The moisture transfer coefficient for interior surfaces is 2x10⁻⁸ s/m. The properties of aerated concrete and other details of these cases can be found in the work aforementioned. Figures 1 and 2 show the comparison between the analytical humidity without moisture buffering at walls.

![Figure 1: Room relative humidity without moisture buffering at walls.](image-url)
Test case details for parametric analysis

In this work, the aforementioned BESTEST geometry has been selected for carrying out hygrothermal simulations. This is a basic geometry which is chosen to avoid complex constructional details and represent a base case for the physical phenomena to be studied. Several authors have taken this geometry for performing hygrothermal analysis (Qin et al. (2011), Tran Le et al. (2016), Zhang et al. (2017), Barclay et al. (2014)).

The test building is conditioned from 09:00 h to 17:00 h with a moisture generation rate of 500 g/h. Internal gains and outdoor conditions are assumed as per Zhang et al. (2017). A constant air change rate (ACH) is maintained in the building throughout the day. The air change is varied from 0.5 to 2.5 h⁻¹ for parametric study. An air-conditioning system maintains the indoor space temperature between 20 °C and 26 °C while the relative humidity is maintained between 40-60 %. To observe the effect of outdoor conditions, five cities in different climate zones of India were considered. The cities selected are: Ahmedabad (hot-dry), Mumbai (warm-humid), Bangalore (temperate), Dehradun (cold) and Delhi (composite). Respectively, these cities/climates are abbreviated in this article with HD, WH, TM, CD, CM.

Detailed hygrothermal properties of building materials such as porosity, initial water content, sorption isotherm, vapour diffusion resistance, and liquid transport coefficients, are required to conduct hygrothermal simulations. In the open literature, there is a lack of information about detailed hygrothermal properties of common building materials in India like brick and cement plaster. Therefore, research on hygrothermal characterization of typical building materials in India is necessary. For the current work, hygrothermal properties for materials such as concrete, plasterboard and spruce wood have been taken from the EnergyPlus (2016) database. The three different building wall types considered in this work are shown in Table 1.

Table 1: Wall construction.

<table>
<thead>
<tr>
<th>Wall layer materials (outside to inside)</th>
<th>Thickness (mm)</th>
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<tbody>
<tr>
<td>Concrete</td>
<td>150</td>
</tr>
<tr>
<td>Concrete + Plasterboard</td>
<td>150+12</td>
</tr>
<tr>
<td>Concrete + Spruce</td>
<td>150+12</td>
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Results and discussion

Free-floating mode

To identify the basic differences in HT and HAMT models simulations are firstly carried out in the free-floating mode. In this mode, the building is simulated without any set point for indoor temperature and relative humidity. The cases considered are: a) concrete wall simulated with thermal-only model (C-HT); b) concrete wall with hygrothermal model (C-HAMT); c) concrete wall and inner spruce layer with hygrothermal model (C+S-HAMT). The weather conditions for these cases correspond to the hot and dry region of India. Figure 3 shows the indoor relative humidity in three different cases.

It is observed from Figure 3 that the indoor relative humidity reaches highest value of 99 % for case a. When HAMT model is used (i.e., case b), the maximum relative humidity is about 88 %. This amounts to a reduction of 10 % when compared to case a. With the use of inner spruce layer, i.e., case c, the maximum humidity is limited to 82 %. This is a difference of 16.5 % when compared to case a. The difference in 3rd and 1st quartile values of indoor humidity reduces from 20 in case a to 15 in case c. When compared to case a, the reduction in difference of maximum and minimum values of indoor relative humidity for case b is 18 %. The same for case c with respect to case a is around 27 %. Thus, the relative humidity values are lower during moisture increase and higher during moisture reduction in the room.

To notice the effect of moisture absorption/desorption at wall surfaces, difference in indoor relative humidity between case b and case a is calculated. This difference, separated in bins of different sizes is plotted against the corresponding hours in Figure 4. The difference in indoor relative humidity between case c and case a is also calculated and separated into bins to explore the moisture buffering effect of inner spruce layer. With spruce layer the number of hours in bin size of 2.5 to 5 reduce by 30 % and those in the bin size from 5 to 7.5 reduce by 12 %. However, in the bin size greater than 7.5 the number of hours increase from 503 to 1433 (i.e., by 185 %). The above observations can be explained by the moisture buffering effect of the building walls accounted in the HAMT model. Furthermore, this moisture buffering effect increases with hygroscopic nature of spruce wood.
This would directly reduce the heating required to reduce humidity if a humidity control is employed.

**HVAC mode**

In the HVAC mode, simulations are carried out with a HVAC system maintaining the aforementioned set points for temperature and relative humidity. Firstly, the results for the building with 150 mm concrete walls having no interior surface finish are presented. Figure 5 shows the absolute values of increase in cooling energy and decrease in heating energy due to HAMT model. Cooling energy increases in all cases. The absolute value of this increase is the lowest (176 kWh) for cold climate and varies between 250 to 290 kWh for other climate zones. The total cooling energy requirement in all climates ranges from 15600-23000 kWh. In all cases, the relative percentage of increase in cooling energy due to the HAMT model is less than 2%.

The heating energy requirement with HT and HAMT models in different climate types is shown in Figure 7. The relative percentage decrease due to HAMT model is also indicated in this figure. For temperate (TM), composite (CM) and cold (CD) climates the relative differences are around 20 %. The absolute difference of around 300 kWh is obtained in cold climate. Although the relative percentages are higher for warm-humid (33 %) and hot-dry (42%), the absolute differences are less than 100 kWh. Figure 8 shows the season wise heating energy demand for hot-dry climate with HT and HAMT models.

Heating energy due to HAMT model reduces in call climate. Unlike the cooling energy increase, reductions in heating energy are substantial and vary between 18 to 42 %. This reduction is between 68-78 kWh for hot-dry and warm-humid climates. For temperate and composite climates the heating energy reduces by around 160 kWh. Highest reduction, of 300 kWh, is obtained in cold climate.

To investigate the effect of envelope surface area and volume on moisture transfer interactions, cases with different building sizes were simulated. With respect to the test case (8mx6mx2.7m), all the three dimensions are halved in one case and doubled in another. Both sensible and latent loads were added proportional to the floor area. Figure 6 shows the increase in cooling energy and decrease in heating energy with HT and HAMT models for hot-dry region. Irrespective of the floor area, the percentage increase in cooling energy due to HAMT model is less than 2.0 %. The decrease in heating energy for smallest floor area (12 m²) is 37 % and that for the largest floor area (192 m²) is around 30 %.
for which the above difference falls in a given bin is shown in Figure 9. The year is divided into three parts i.e., November to February, March to June, and July to October. The number of hours in a particular bin and period are also indicated.

During the relatively cold period, i.e., from November to February, the total number of hours in bin size between 2.5 to 5 are 26% higher than the rest of the months considered together. This represents 50% of the hours during these months in this bin. Also, the number of hours in the colder period for bin sizes greater than 5 are 198. This is more than twice the number of hours in rest of the year and amounts to around 65% of the hours in this bin. Figure 10 the indoor relative humidity variation in the month of January. With the HAMT model, the indoor relative humidity values are lower than those predicted by the HT model. It is seen that the relative humidity without moisture buffering at walls, i.e., with HT model is higher than the HAMT model by up to 10% and this occurs during the moisture generation period from 09:00 h to 17:00 h.

The foregoing observations show that absorption of moisture at walls considered in the HAMT model helps in regulating the indoor humidity levels. This in turn affect reduces the heating requirement in all climate types. The heating reduces in colder months when HAMT model is employed. This indicates that the savings are mainly due to the reduction of reheating to maintain the set points of relative humidity. The differences in heating energy are lesser in months of July and August when the ambient air is very humid and moisture buffering is not effective due to saturation of the inner wall material and little scope for regeneration (drying) with ambient air. However, in relatively cooler months the effect of moisture absorption at walls is higher. Also, in hot and humid period, cooling and dehumidification reduces the reheat to be provided. Similar trends are observed for cities in other climate zones, i.e., moisture buffering is more effective in the relatively cooler and drier parts of the year.

As far as the cooling energy is concerned, its increase with HAMT model is due to higher envelope gains. Higher envelope gains result from higher thermal conductivity due to moisture transfer in the building material. From the energy point of view, the HAMT model predicts insignificant differences in cooling energy. Similar trends are obtained for spaces with higher building floor/surface areas. One of the reasons for this could be the modelling of rain in EnergyPlus (2016). The energy plus weather (epw) files have the rain indicators which note the occurrence of rain and its magnitude range. By activating the rain indicator option, in case of surface wetting by rain, the liquid transport coefficients should change from redistribution to suction. Suction liquid transport coefficient, usually higher than redistribution would further increase the U-value of the building material. However, it was observed that the results of simulations did not change by activation of the rain indicator option.

**Effect of different interior wall finish**

The differences between thermal-only (HT) and hygrothermal models (HAMT) for interior finishes of 12mm thick plasterboard and spruce over concrete are shown in Figures 11 and 12 respectively. With plasterboard finish, the reduction in heating requirement is maximum (283 kWh) in cold climate and minimum (3 kWh) for temperate climate. For spruce wood interior finish, the reduction in heating requirement is maximum (241 kWh) in cold climate and minimum (44 kWh) for warm and humid climate. Thus, the overall trends, i.e., reduction in heating energy and increase in cooling energy, are observed for all three wall constructions. Direct comparison of heating and cooling energy requirement cannot be made between the three wall types because the U-value for these cases is different. However, differences in cooling and heating energy with climate type can be noticed. The energy requirements reduce with the use of interior finish layer.
Reduction in overall cooling energy requirement is shown in Figure 13. With plasterboard the reduction is around 10% and with spruce finish it is around 20% for all climate types. This is due to the lower thermal conductivity of spruce (0.09 W/m-K) than plasterboard (0.2 W/m-K).

The reduction in heating energy for all climates with plasterboard and spruce is shown in Figure 14. Unlike cooling energy, in this case the savings are different for different climates. This is because heating energy is related to the moisture buffering effect of the finish material in the respective climate. Reduction due to plasterboard is less than 3.5% for temperate and warm-humid climates. For hot-dry climate the reduction is around 30%. For hot-dry region the reduction is about 42%. For the cooler composite and cold climates, the reduction is of the order of 31%.

**Effect of air changes per hour (ACH)**

The effect of varying air change rate (ACH) on the cooling and heating energy requirements for different climate zones is shown in Figures 15 and 16 respectively. In all cases, cooling energy requirement increases with increase in air change rate. As expected, cooling energy is highest for hot-dry climate. It increases from 22800 kWh at 0.5 h⁻¹ to 26000 kWh at 2.5 h⁻¹. This corresponds to an increase of around 14%. The lowest values occur in cold climate. In this case, when the ACH is varied from 0.5 to 2.5 h⁻¹, the cooling requirement increases from 15600 to 17400 kWh. The relative increase is about 12%. Cooling energy with HAMT model is higher than that for HT model in all cases. However, the absolute differences vary between 200-400 kWh. When compared to the overall cooling requirement the relative differences are below 2%.
The heating energy requirement also increases with increasing air change rate. When the air change rate is varied from 0.5 h\(^{-1}\) to 2.5 h\(^{-1}\), the heating energy for temperate, composite and cold climates increases by 123\%, 53\% and 58\% respectively. As compared to the HT model, the heating energy reduces when HAMT model is employed. For hot-dry and warm-humid climates, the reduction in heating energy due to HAMT model increases up to air change rate of 1.5. Thereafter, for higher air change rates the reduction in heating energy achieves a constant value of around 150 kWh. Similarly, in case of temperate climate reduction in heating energy is not substantial for values of air change rates more than 1.0 achieving values of around 220 kWh. For composite climate (CM), the reduction in heating energy is around 150 kWh for all air change rates. For cold climate, the reduction in heating energy starts reducing from 300 kWh at 0.5 h\(^{-1}\) to 200 kWh at 2.5 h\(^{-1}\).

The reduction in heating energy due to moisture buffering is counterbalanced by need of heating due to higher air flow rates at lower temperatures in the cold climate. In other climates moisture buffering achieves its maximum limit and ceases to increase for higher air flow rates. As far as heating energy is concerned, the reduction in heating requirement always exits with HAMT model. One of the reasons of such a behaviour is the well mixed zone assumption and therefore a single temperature and relative humidity for the entire zone. Moisture buffering will be always calculated due to the difference in relative humidity of walls and indoor. However, in reality not all the air volume will come in contact with the room walls to be able to exchange moisture. So, the differences between the two models could be on the higher side for higher air change rate.

**Conclusion**

In this work, hygrothermal (HAMT) and thermal-only (HT) models of EnergyPlus (2016) have been employed for simulating a building in five different climates of India. The study considers the effect of different wall constructions and air change rates on the heating and cooling requirement predicted by the above models. With the HAMT model, there is a reduction in heating requirement for all climates due to the consideration of moisture transfer between indoor air and wall surfaces. The reduction in heating energy for cold, temperate and composite climate could be up to 20\%. The increase in cooling energy due to HAMT model, i.e., by considering moisture transfer through the envelope is less than 2\% in all climatic conditions and wall constructions. The major contributors of cooling load i.e., like solar gains, internal gains and gains due to air change rate remain the same in both HT and HAMT models. Thus, from cooling energy point of view, the moisture transfer due to air changes completely outweighs the moisture transfer through the building envelope. As compared to plasterboard, an interior layer of spruce on concrete is effective in reducing both heating and cooling requirements for all climate zones. With spruce, cooling energy requirement can be reduced by 20\% and heating energy requirement is reduces in the range of 25-40\%.

**References**


