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Evaluation of Different Thermal Models in EnergyPlus for Calculating Moisture Effects on Building Energy Consumption in Different Climate Conditions

Jun Yang[a], Hao Fu[a], Menghao Qin[a,]*

School of Architecture and Urban Planning, Nanjing University, Hankou Road 22, Nanjing 210093, P.R.C.

Abstract

The calculation of building energy consumption is needed in all architecture design projects. Building simulation software is used to predict the indoor air temperature and relative humidity as well as the building's heat loads. The calculation of accurate heat load requires calculating coupled heat and moisture transfer in building envelopes and the hygrothermal interactions between the envelopes and the environment. However, the moisture effects of building envelopes are often neglected. This would bring much inaccuracy to the simulation results. Based on different calculation methods, many numerical building energy simulation programs have been developed. This paper evaluates the accuracy and the applicability of three thermal models in EnergyPlus (CTF-Conduction Transfer Function model, HAMT-Combined Heat and Moisture Transfer model, EMPD-Effective Moisture Penetration Depth model) for calculating moisture effects on building energy consumption in different climate conditions. The effects of different room infiltration rate on the accuracy of different models are also analyzed.

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Keywords: Thermal models; Moisture effects; Building energy consumption; EnergyPlus;

1. Introduction

The moisture transfer through building envelopes and between the building envelope and the indoor environment is important. According to [1], about one third of the moisture generated in the room would be absorbed into the

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* Corresponding author. Tel.: +86-25-83597332
E-mail address: mqin@nju.edu.cn

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building envelope when the moisture content in the indoor air is high. While the moisture in the indoor air is low, the moisture would be released into the indoor air. Therefore, the moisture absorption/desorption of building envelopes helps to buffer the moisture content of the indoor air. Consequently, as much energy is used in HVAC systems for dehumidification, the moisture buffering capacity of building envelopes may affect the cooling energy consumption of buildings, especially when dehumidification process is needed. Overall, the accurate calculation of building energy consumption should take the moisture transfer together with heat transfer through building envelopes and between the building envelope and the indoor environment into account.

However, the moisture effects of building envelopes are neglected in a lot of building simulation programs. These programs are developed with some simplified methods (e.g. Conduction Transfer Function model-CTF) [2] and only calculate the heat transfer of building envelopes. These methods calculate rapidly, but may bring much inaccuracy into the simulation results of indoor hygrothermal conditions and building energy consumption [3]. Researchers have also developed finite-difference methods. The methods calculate the coupled heat and moisture transfer inside building envelopes and the interactions between the envelope and the environment (e.g. Combined Heat and Moisture Transfer model-HAMT) [2]. However, high level of measuring technologies and specific experiences are needed to acquire some parameters used in the methods. The calculation process also requires 10^2-10^4 [4] more computation time than the simplified models. These methods were originally developed for the drying of sand and for the research of building materials, and they are not suitable for building energy consumption simulation during the preliminary stage of architecture design. With the above problems, simpler models (e.g. Effective Moisture Penetration Depth model-EMPD) [2] that calculate the moisture effect of building materials with both fast solution time and reasonable accuracy have been developed. The method was originally developed by Cunningham [5,6] and Kerestecioglu et al. [7]. It assumes a thin layer close to the wall surface behaves dynamically and exchanges moisture with the air. The depth of this thin layer is called moisture penetration depth and can be calculated from moisture capacity and vapor permeability. However, the method has some limitations. First, measuring the moisture penetration depth needs much time and labor. Second, the thin layer in the method only accounts for short-term moisture change. It may bring some inaccuracy when it is used for simulating long-term moisture change such as seasonal change. [8]

The purposes of this paper are to evaluate the accuracy and the applicability of different thermal models for calculating moisture effects on building energy consumption in different climate conditions. All three models (CTF, HAMT, EMPD) are simulated for three climate conditions (hot/humid, temperate, hot/dry). The effects of different room infiltration rate on the accuracy of different models are also analyzed. EnergyPlus is used in this paper as it is the most widely used building energy consumption simulation software [9] and is the platform that has all the above thermal models.

2. Mathematical models

Description of the three thermal models can be found in [4]. The details of the three models can be found in [2]. The governing equations of the heat and moisture balance of the air-conditioned space are described as follows [3,10]:

$$\rho C_{\mathrm{p}} V \frac{\partial T_{\mathrm{i}}}{\partial \tau} = \sum_{\mathrm{j}} A_{\mathrm{j}} \alpha_{\mathrm{j}} \left(T_{\mathrm{j}} - T_{\mathrm{i}} \right) + nV\rho C_{\mathrm{p}} \left(T_{\mathrm{o}} - T_{\mathrm{i}} \right) + Q_{\mathrm{in}} + Q_{\mathrm{HVAC}} \tag{1}$$

$$V \frac{\partial v_{\mathrm{i}}}{\partial \tau} = \sum_{\mathrm{j}} A_{\mathrm{j}} g_{\mathrm{in,j}} + nV \left(v_{\mathrm{o}} - v_{\mathrm{i}} \right) + M_{\mathrm{in}} + M_{\mathrm{HVAC}} \tag{2}$$

where ρ is the density of air (kg/m^3), C_p is the heat capacity of air (J/kg K), V is the volume of the room (m^3), τ is the time (s), A_j is the surface area (m^2), α_j is the heat transfer coefficient (W/m^2 K), T_j is the surface temperature (K), T_i is the indoor air temperature (K), T_o is the exterior air temperature (K), n is the air change rate (h^{-1}), Q_{in} is the internal heat gains from people, lights and equipment (W), Q_{HVAC} is the heat gains or loss due to the HVAC system (W), v_i is the vapor content of the interior air (kg/m^3), v_o is the vapor content of the exterior air (kg/m^3), $g_{in,j}$ is the moisture flux into the room (kg/s m^2), M_{in} is the internal moisture gains (kg/h), M_{HVAC} is the moisture gains or loss due to HVAC system (kg/h).

3. Model validation

The HAMT model was validated by using measured data from a field measurement and the simulation results of another combined heat and moisture model (HAM-QIN). The HAM-QIN model is implemented into Matlab-Simulink and the details of the model can be seen in [3,11]. The CTF model and the EMPD model are also used in the model validation to compare with the simulation results of the two HAM models and the measured data. The details of the field measurement and simulation settings can be found in [11].

Fig. 1 shows the measured and simulated indoor air temperature and relative humidity. It can be seen that the indoor air temperature simulation results of the HAMT model and the HAM-QIN model are in good agreement with the measured data, and are more accurate than the simulation results of the other two models. As the simulation of indoor air relative humidity is much more complex than the simulation of indoor air temperature, the simulation results of the HAM-QIN model has much inaccuracy when the indoor air relative humidity drops as the air is dehumidified by the cooling system, as the dehumidification system is not the same as the systems in EnergyPlus. Among the other three thermal models in EnergyPlus, the HAMT model is the most accurate model. Therefore, the HAMT model is assumed to be the correct model for the simulation analysis among different models in the case study.

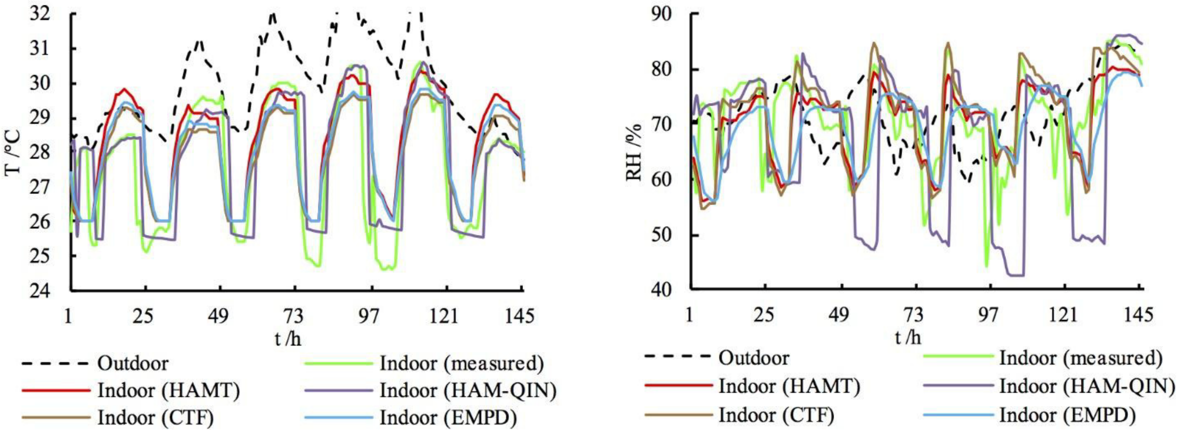

Fig. 1. measured and simulated indoor temperature and relative humidity (July 16-21, 2013).

4. Case study

The test room was then applied to test the simulation accuracy of the thermal models and evaluate the applicability of these models for calculating moisture effects on building energy consumption in different climate conditions. The simulations were run in EnergyPlus under EnergyPlus Weather Data [12] of three different climates: hot/humid (e.g. Nanjing), temperate (e.g. Paris), hot/dry (e.g. Phoenix). Two adults were assumed to be sleeping inside the bedroom from 10:00 pm to 8:00 am of the next day. The construction details and other simulation details were based on the results from the field measurement. The infiltration rates were 0.5 ACH, 1 ACH, 2 ACH and 5 ACH. During the occupied period, the air-conditioner was set to be turned on for cooling when the indoor temperature was over 26 °C and the dehumidification process was set to be turned on when the indoor relative humidity was higher than 65%.

4.1. Hot/Humid Climate (Nanjing)

The simulated indoor temperature and relative humidity of Nanjing with 0.5 ACH infiltration rate are shown in Fig. 2. The outdoor temperature of Nanjing fluctuates from 26 ºC to 36 ºC and the indoor temperature is above 28 ºC. Cooling is needed every day. When cooling is turned on at night, the indoor temperature drops to 26 ºC. Temperature simulation results of HAMT model are 0.5-1 ºC higher than CTF model and EMPD model, as the HAMT model takes the heat of absorption and desorption into account.

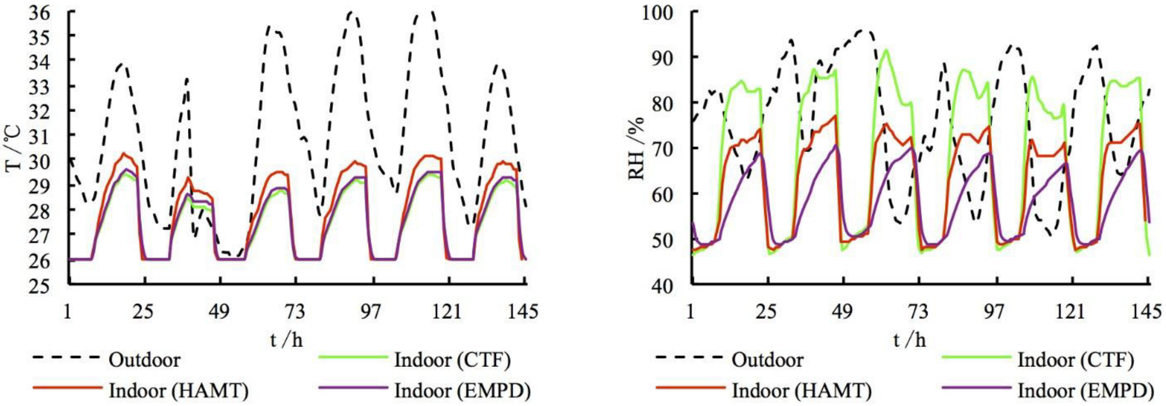

Fig. 2. simulated indoor temperature and relative humidity of hot and humid climate (Nanjing, 0.5 ACH, July 16-21).

The hygroscopic building materials in the HAMT model will absorb moisture during daytime as the indoor air relative humidity is higher than 70% for most daytime. The absorption heat released into the indoor air causes the temperature of indoor air in the HAMT model to be higher than the other two models. As a result, when cooling system works at night, the overall sensible load of HAMT model is higher than EMPD model, and EMPD model higher than CTF model. However, the cooling process would dehumidify the indoor air and the relative humidity will drop to around 50%. During this time, the hygroscopic materials in the HAMT model release part of the absorbed moisture into the indoor air. The moisture release process absorbs heat from the indoor air, helps cool the indoor air and decreases the sensible peak load of the HAMT model. The released moisture from the hygroscopic materials and the moisture transferred through the building envelopes also brings more latent load to the cooling and dehumidifying system in the HAMT model. While as the indoor air relative humidity of CTF model is higher than HAMT model, the latent peak load of CTF model is higher than HAMT model.

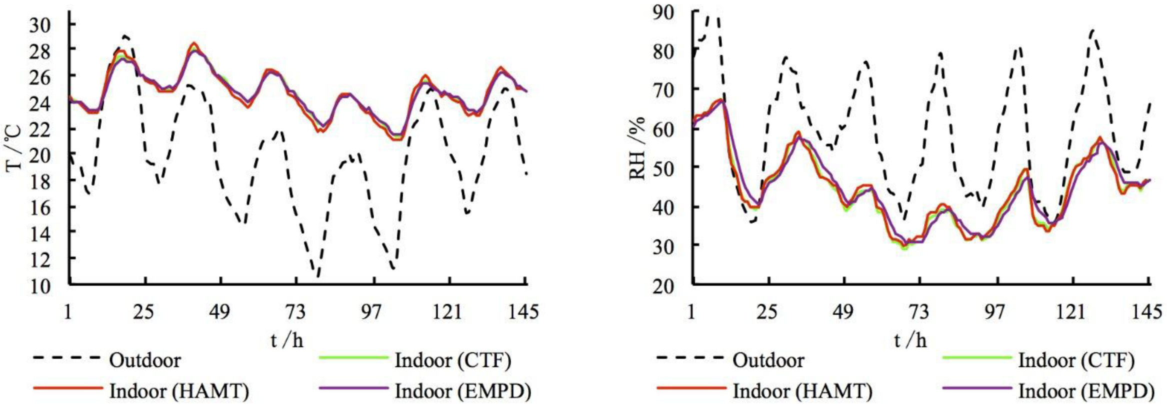

Fig. 3. simulated indoor temperature and relative humidity of temperate climate (Paris, 5 ACH, July 16-21).

4.2. Temperate Climate (Paris)

Fig. 3 shows the simulated indoor temperature and relative humidity of Paris with the infiltration rate of 5 ACH. The temperature of Paris is not very high (around 24 °C) during daytime but is low (around 14 °C) at night. Ventilation is used for cooling to save energy. With the interior heat production rate of 135 W, the indoor temperature is higher than 22 °C. The temperature and relative humidity results of the three models are mainly the same. Therefore, the moisture effects of building materials are not obvious under this climate.

4.3. Hot/Dry Climate (Phoenix)

Fig. 4 is the simulated indoor hygrothermal conditions of Phoenix with the infiltration rate of 0.5 ACH. The outdoor temperature of Phoenix is very high and it fluctuates from 28 °C to 40 °C. The indoor air temperature is from 26 °C to 32 °C. Temperature simulation results of HAMT model are 1 °C higher than CTF model and EMPD model. The outdoor relative humidity is low and it fluctuates from 20% to 50% everyday. As there is an interior moisture source in the simulation cases, the indoor relative humidity is higher than 30%. Dehumidification is not needed in these cases.

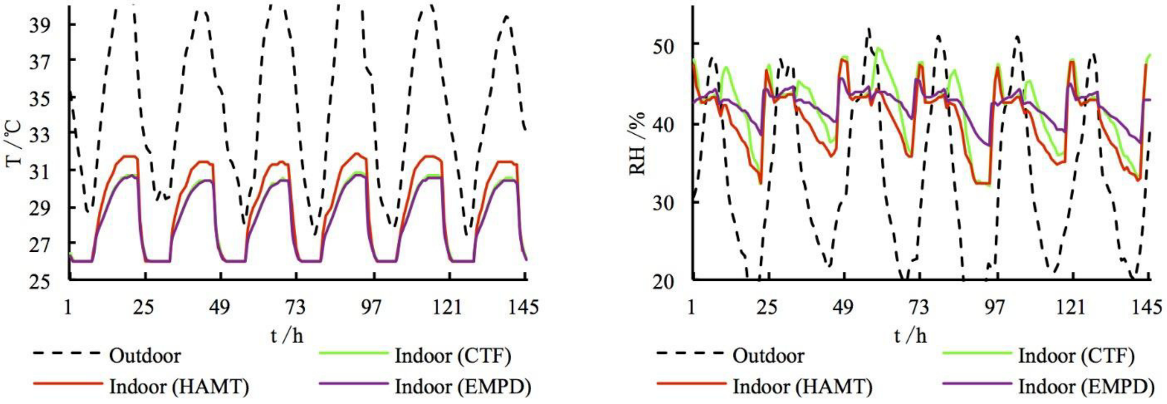

Fig. 4. simulated indoor temperature and relative humidity of hot and dry climate (Phoenix, 0.5 ACH, July 16-21).

As the hygroscopic building materials in the HAMT model are dry when the simulation starts, they slowly absorb moisture all day despite of the low relative humidity. Later when the air relative humidity is high at night, the hygroscopic materials absorb moisture at night and release some of the moisture back to the indoor air during daytime when the indoor relative humidity is low. Like the cases of the hot/humid climate, the absorption heat released into the indoor air makes the indoor temperature in the HAMT model to be higher than the indoor temperature of the CTF model and EMPD model. As the building materials absorb moisture at night, the indoor relative humidity of the HAMT model is lower than the indoor relative humidity of the CTF model and the EMPD model.

5. Discussion

The peak cooling load of the three models with different infiltration rates are calculated as the air-conditioning systems are selected according to the cooling peak load of the building. The peak cooling load simulation inaccuracy are shown in Table 1. Afterwards, the applicability of the three models in different climate conditions are analyzed.

Table 1. Peak cooling load simulation inaccuracy of CTF model and EMPD model (%).

Infiltration rates	Peak load type	Hot/Humid		Temperate		Hot/Dry	
		CTF	EMPD	CTF	EMPD	CTF	EMPD
0.5 ACH	Sensible	4.0	-4.0	22.7	27.3	0.0	9.7
	Latent	10.0	40.0	0.0	133.3	0.0	100.0
	Total	0.0	13.3	16.7	33.3	0.0	12.9
1 ACH	Sensible	8.7	4.3	25.0	25.0	3.2	12.9
	Latent	9.1	45.5	0.0	100.0	0.0	33.3
	Total	3.3	13.3	23.8	33.3	3.2	12.9
2 ACH	Sensible	9.1	4.5	26.7	26.7	3.1	9.4
	Latent	0.0	46.2	0.0	200.0	0.0	50.0
	Total	3.2	9.7	25.0	31.3	3.1	9.4
5 ACH	Sensible	9.5	4.8	16.7	0.0	6.1	12.1
	Latent	0.0	21.1	0.0	-100.0	0.0	28.6
	Total	6.2	12.5	33.3	16.7	6.1	12.1

For hot/humid climate, the indoor relative humidity is not high because indoor air is dehumidified by the cooling systems. The hygroscopic materials used in the HAMT model effectively moderate the indoor relative humidity but slightly change the cooling loads. The simulation inaccuracies of sensible peak load and latent peak load of the CTF model are about 5%-10% with different infiltration rates. This means the CTF model is capable of simulating building energy consumption and will bring only a little inaccuracy. The simulation inaccuracy of sensible peak load of the EMPD model is also within 10% but the simulation inaccuracy of peak latent load of the EMPD model varies from 20% to 45%. Therefore, the EMPD model can be used for thermal simulation but should not be used for simulating moisture effects of hygroscopic building materials. In conclusion, the HAMT model is the best choice for simulating indoor air temperature and relative humidity and the CTF model is the best choice for the building peak cooling load simulation model in this climate.

For temperate climate, as cooling and dehumidification are not needed in most of the time, the actual differences among the cooling loads of different models are small and the inaccuracy of the two models are relatively high. The inaccuracy of the latent peak load CTF model is about 15%-30% and the inaccuracy of the EMPD model is from about 25%-100%. Therefore, the HAMT model is the best model in this climate.

For hot/dry climate, the cooling systems do not dehumidify the indoor air as the indoor relative humidity is low. The hygroscopic materials used in the HAMT model and EMPD model absorb moisture when cooling is available. The simulation inaccuracies of peak loads of the CTF model are mainly within 5% under different infiltration rates. In such cases, the CTF model is the best model for the simulation analysis.

6. Conclusions

Based on different calculation methods, many numerical building energy simulation programs have been developed. Simplified methods like CTF calculate rapidly but do not calculate the coupled heat and moisture transfer inside the building envelopes. The finite-difference methods like HAMT calculate the coupled heat and moisture transfer inside building envelopes and the interactions between the envelope and the environment, but require much more computation time than the simplified models. A comprise (EMPD) between the two methods calculates fast but brings inaccuracy. This paper analyzed the simulation accuracy of three thermal models in different climate conditions (hot/humid, temperate, hot/dry) through calculating the building energy consumption in EnergyPlus and evaluated the applicability of these models for calculating moisture effects on building energy consumption.

For hot and humid climate, hygroscopic materials used in the HAMT model will effectively moderate the indoor relative humidity but slightly change the cooling loads. The CTF model is the best choice for simulating peak cooling loads, while the HAMT model is the best choice for simulating indoor air temperature and relative humidity. For temperate climate, the actual differences among the cooling loads of different models are small. The inaccuracy of the CTF model and the EMPD model is large. The HAMT model is the most suitable model for this climate among the three models. For hot and dry climate, the indoor relative humidity is low and the hygroscopic materials have limited moisture effects. The CTF model is the best choice for the building energy consumption simulation analysis.

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