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Application Method of a Simplified Heat and Moisture Transfer Model of Building Construction in Residential Buildings

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Abstract: Several building energy simulation programs have been developed to evaluate the indoor conditions and energy performance of buildings. As a fundamental component of heating, ventilating, and air conditioning loads, each building energy modeling tool calculates the heat and moisture exchange among the outdoor environment, building envelope, and indoor environments. This paper presents a simplified heat and moisture transfer model of the building envelope, and case studies for building performance obtained by different heat and moisture transfer models are conducted to investigate the contribution of the proposed steady-state moisture flux (SSMF) method. For the analysis, three representative humid locations in the United States are considered: Miami, Atlanta, and Chicago. The results show that the SSMF model effectively complements the latent heat transfer calculation in conduction transfer function (CTF) and effective moisture penetration depth (EMPD) models during the cooling season. In addition, it is found that the ceiling part of a building largely constitutes the latent heat generated by the SSMF model.



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Keywords: simplified heat and moisture transfer; steady-state moisture flux; effective moisture penetration depth; sensible and latent heat transfer; prediction error

1. Introduction

At present, the issue of energy consumption reduction in buildings is increasing. The heating, ventilating, and air conditioning (HVAC) system in buildings uses a large portion of the total building energy, i.e., ~40% [1]. Consequently, for saving building energy consumption, the demand for high-insulation and airtight buildings with highly efficient windows, such as passive houses, is increasing. This change in envelopes makes not only temperature but also humidity in buildings impact the energy consumption. Whole-building simulation can be used to predict the amount of sensible and latent load required to maintain the temperature and humidity set-points under fluctuating external and internal environment conditions. The heat flux generated from the internal surface of the building envelope largely affects the cooling and heating loads. Most of the evaluated models for building energy consumption that consider indoor conditions and air conditioning system requirements often neglect the transport and storage of moisture in porous building materials [2].

Moisture effects, such as diffusion and vapor sorption–desorption from materials, are typically ignored due to the significant increases in model complexity, computation time, and insufficient moisture material data. However, this negligence can lead to inaccurate evaluation of the indoor conditions and sizing of the HVAC system. Barbosa and Mendes [3] showed that the negligence of moisture effects can result in an inaccurate prediction of the air-conditioning loads and indoor environmental conditions. Mendes et al. [2] showed that ignoring the moisture influence in the model may lead to overestimating the conduction peak loads up to 210% and underestimating the yearly integrated heat flux

up to 59%. Qin et al. [4] discovered reductions of 1.7–5.8% and 8–16% in the amounts of heating energy consumption cooling energy used in the hygrothermal transfer model, compared to those predicted by the heat transfer model for three locations: Guangzhou, Paris, and Phoenix. In terms of cooling energy, hygroscopic materials can reduce the indoor humidity, and consequently, the indoor enthalpy. In terms of the heating energy, the hygroscopic materials release the heat of moisture. Ozaki et al. [5] compared the energy consumption of a residential building using two method models: with and without sorption and desorption calculations of the wall. With the application of the general heat transfer model, the latent cooling and heating loads were increased by ~50% and 7%, respectively. Wang et al. [6] compared the cooling and heating loads of a whole building with and without the hygrothermal transfer models for the main cities in China and found that the maximum error of cooling load was 20% and that of heating load was 22%.

The heat and moisture transfer model used to reduce these errors has been studied and developed from a simplified model to a detailed model. The simplified models, which include the effective moisture penetration depth (EMPD) model and moisture buffer value (MBV) model [7], have the advantages of simple input conditions and relatively short computation time, but have the disadvantage of producing a resultant error compared to the detailed models [8,9]. On the other hand, the detailed model, which is a coupled heat and moisture transfer (HAMT) model, can be evaluated more accurately by calculating the moisture transfer characteristics (absorption/desorption and capillary suction) of the material. However, it is not widely used because of the difficulty of user accessibility and calculation time, owing to the model's complexity [10,11]. The HAMT model, which uses the finite difference, is more realistic than the simplified models, but the entire building simulation requires many hygroscopic material properties, including moisture contents, liquid suction coefficient, liquid transport coefficient, and water vapor diffusion. The complexity of the model and the lack of knowledge of building material properties may lead to significant uncertainties in the overall results. In addition, the detailed model takes longer to compute than the simplified model because it is necessary to analyze the transport of moisture and heat as material properties with non-linearities, it is necessary to repeat sub-iterations to converge, and Jason [10] showed that the simulation run time takes 10^2 – 10^4 times over in a single-zone building. This shows that for complex buildings, more calculation time is required.

In order to overcome the limitation of calculation time, which is a disadvantage of the detailed heat and moisture transfer model, various numerical analysis methods have been studied. Gasparin et al. [12] showed a study that drastically reduces the simulation time while guaranteeing accuracy compared to both classical EULER implicit and CRANK-NICOLSON scheme in the analysis of heat and humidity movement using a spectral reduced-order model (Spectral ROM). Explicit models require very fine time discretization for stability conditions. An improved explicit model study was conducted to overcome these shortcomings. Using the improved explicit analysis method DUFORT-FRANKEL, compared to the classical EULER implicit and explicit scheme, the calculation time was significantly reduced [13,14].

The objective of this paper is to propose a simplified model that can reduce errors incurred by the detailed model. In this paper, a steady-state moisture flux (SSMF) model is proposed to calculate sensible and latent loads through envelopes of buildings. This model is based on both Glaser's method [15] and the conduction heat transfer model and compared with the coupled heat and moisture transfer model. The SSMF model is applied to both the conventional heat transfer model and a simple heat and moisture transfer model to compare the error reduction obtained with the combined heat and moisture transfer model. Then, the proposed model is applied to evaluate the moisture performance of the building assemblies and envelopes in different climate zones.

The rest of this paper is structured as follows. In Section 2, we describe the conventional combined heat and moisture transfer model in building energy simulation. Section 3 describes the SSMF model and its application. Section 4 discusses the simulation analy-

sis of the SSMF model and existing model. In Section 5, we present sensible and latent heat transfer from the inside surface and inside surface temperature and discuss their implications. Finally, Section 6 summarizes the key findings of the study.

2. Computational Methods for Coupled Heat and Moisture Transfer

2.1. Mass Balance Equation

Not only indoor air temperature but also indoor air humidity is an important factor that influences the energy consumption of buildings and occupants' thermal comfort in buildings. Indoor air humidity is affected by factors such as moisture sources (from human and equipment), ventilation and infiltration/exfiltration, and sorption of building materials (envelope and furnishings). The transient moisture balance for the indoor air in a room in terms of partial pressure of water vapor [16] is expressed as follows:

$$\frac{V_z}{R_v T_z} \frac{dp_{v,z}}{d\tau} = \dot{M}_i + \dot{M}_{sys} + \frac{\dot{V}_{inf}}{R_v T_z} (p_{v,amb} - p_{v,z}) + \sum_{j=1}^N A_j \beta_j (p_{v,surf} - p_{v,z}) \quad (1)$$

where V_z is the zone air volume, m^3 ; R_v is the gas constant for water vapor, $J/kg \cdot K$; T_z is the zone air temperature, K ; $V_z / (R_v T_z)$ is the moisture capacity of the zone air; $p_{v,z}$ is the partial vapor pressure of the zone air, Pa ; τ is time, s ; $\dot{M}_i$ is the internal gain moisture in the zone, kg/s ; $\dot{M}_{sys}$ is the moisture addition (or removal) by the HVAC system, kg/s ; A_j is the inside wall surface, j , m^2 ; $\dot{V}_{inf}$ is the volume flow rate of infiltration, m^3/s ; $p_{v,amb}$ is the partial vapor pressure of outdoor air, Pa ; $p_{v,surf}$ is the partial vapor pressure of the inside wall surface, Pa ; and β_j is the water vapor transfer coefficient, $kg/m^2 \cdot s \cdot Pa$.

The term on the left-hand side describes the vapor storage in air. The right-hand side shows the indoor vapor produced by people and process loads, vapor addition by the HVAC system, and vapor gains by infiltration. The last term on the right side is the convective vapor transfer from the zone air to the interior surfaces of the walls. It is determined by the hygrothermal characteristics of envelope materials and the air conditions. The latent heat changes as the water vapor evaporation contributes to the heat balance as well as the mass balance of the air. Hence, the use of coupled heat and moisture transfer is necessary to predict accurate room conditions.

2.2. Simplified Model—Effective Moisture Penetration Model

The simplified model used for calculating heat and moisture transfer in this study is the effective penetration depth (EMPD) model, which is a semi-empirical model combining physics-based and empirical methods [17]. The EMPD model, which was developed by Kerestecioglu et al. [18,19] and Cunningham [20,21], contains both buffer storage and a detailed derivation of the spatially lumped moisture model. Its key assumption is that the thin buffer layer of the hygrothermal material for construction interacts with the indoor air. The moisture storage and transport in the buffer layer have a uniform moisture content and its thickness (d_{EMPD}) is subjected to the period of the moisture variation cycle. The lumped mass transfer equation for the buffer layer in the wall is subject to the period of the moisture variation cycle, as follows:

$$(A \cdot \rho_{matl} \cdot d_{EMPD}) \frac{dU}{d\tau} = A \cdot \beta_z (p_{v,zone} - p_{v,surf}) \quad (2)$$

where U is the moisture content of the material $[kg_{water}/kg_{dry-material}]$, A is the surface area of the material $[m^2]$, d_{EMPD} is the effective moisture penetration depth $[m]$, β_z is the water vapor transfer coefficient $[kg/m^2 \cdot s \cdot Pa]$, $p_{v,zone}$ is the partial vapor pressure of the zone air $[Pa]$, and $p_{v,surf}$ is the partial vapor pressure of the inside wall surface $[Pa]$.

The effective moisture penetration depth of materials, which indicate the moisture content through adsorption and desorption, can be determined using experimental data. It

is related to the period of typical fluctuations (periodic cycling) in the vapor pressure at the wall surface [22]:

$$d_{EMPD} = \sqrt{\frac{\delta \cdot p_{v,sat}(T_{surf}) \cdot \tau_p}{\rho_{matl} \cdot \frac{dU}{d\phi} \cdot \pi}} = \sqrt{D^w \frac{\tau_p}{\pi}} \quad (3)$$

Here, δ indicates water vapor permeability [$\text{kg}/\text{Pa} \cdot \text{m} \cdot \text{s}$], $p_{v,sat}(T_{surf})$ is saturation water vapor pressure at surface temperature [Pa], τ_p is the period of cyclic variation [s], ρ_{matl} is the dry material density [kg/m^3], $dU/d\phi$ is the sorption curve expressed by the water content in relation to relative humidity [$\text{kg}_{water}/\text{kg}_{material}/\text{relative humidity}$], and D^w indicates moisture diffusivity [m^2/s].

The EMPD model, which is defined by the effective moisture penetration depth of the material base on the cyclical humidity load, is also simpler and faster than detailed method models. However, the EMPD model assumes no moisture distribution across the building material; in other words, it overlooks the water vapor transfer between the inside and outside through exterior or interior walls. If the diffusion and convection moisture transport mechanisms are important, as may occur with large moisture gradients across a wall or with relatively porous wall materials, the result obtained from the EMPD approach may not be suitable for evaluating the moisture transfer.

2.3. Detailed Model—Heat and Moisture Transfer Model

The following description discusses the combined HAMT model, which forms the basis for WUFI® [23], ESP-r [24,25], and EnergyPlus [26] simulation programs. This model is based on the hygrothermal building component calculation model, and is a one-dimensional, finite-element, heat, and moisture transfer model [27,28]. This model uses a heat balance equation and a moisture balance equation, both of which are linked with each other through the moisture dependence of thermal conductivity, the heat source term, and the total enthalpy, as well as through the temperature dependence of the moisture flows:

$$\frac{\partial H}{\partial \tau} = \frac{\partial H}{\partial T} \frac{\partial T}{\partial \tau} = \frac{\partial}{\partial x} \left(k^w \frac{\partial T}{\partial x} \right) + h_v \frac{\partial}{\partial x} \left(\frac{\delta}{\mu} \frac{\partial p_v}{\partial x} \right) \quad (4)$$

$$\frac{\partial w}{\partial \tau} = \frac{\partial w}{\partial \phi} \frac{\partial \phi}{\partial \tau} = \frac{\partial}{\partial x} \left(D^w \frac{\partial w}{\partial \phi} \frac{\partial \phi}{\partial x} \right) + \frac{\partial}{\partial x} \left(\frac{\delta}{\mu} \frac{\partial p_v}{\partial x} \right) \quad (5)$$

where $\frac{\partial H}{\partial T} = (c\rho + c_w w)$ is the moisture-dependent heat storage capacity [$\text{J}/\text{m}^3 \cdot ^\circ\text{C}$], $c\rho$ is the volumetric heat capacity of dried material [$\text{J}/\text{m}^3 \cdot ^\circ\text{C}$], c_w is the specific heat capacity of water [$\text{J}/\text{kg} \cdot ^\circ\text{C}$], k^w is the moisture-dependent thermal conductivity [$\text{W}/\text{m} \cdot ^\circ\text{C}$], h_v is the evaporation enthalpy of water [J/kg], δ is the vapor diffusion coefficient in air [$\text{kg}/\text{m} \cdot \text{s} \cdot \text{Pa}$], μ is the moisture-dependent vapor diffusion resistance factor [—], $\frac{\partial w}{\partial \phi}$ is the humidity-dependent moisture storage capacity [kg/m^3], D^w is the moisture diffusivity [m^2/s], and ϕ is the relative humidity [—].

Equation (4) express the heat balance within the material; the last term represents the heat sink or heat sources resulting from the vapor absorption or desorption. Equation (5) expresses the moisture balance; the first term on the right-hand side indicates the liquid water transfer and the last term indicates the water vapor transfer. The liquid water transfer (through surface diffusion and capillary conduction) flux density depends on the gradient the relative humidity by using the Darcy law. In the liquid water transfer, the moisture diffusivity, D^w , strongly depends on the moisture content and represents the moisture flow in the material due to capillary conduction. Fick's law describes the water vapor transfer. In the water vapor transfer, δ/μ is the water vapor permeability of material, and it represents the characteristics of the change in vapor diffusion flux according to the water vapor pressure in the material. The HAMT model accounts for coupled heat and mass transfer in building materials. To determine the temperature and relative humidity of materials in the next time step, the solver computed by iterating the heat and mass balance

equation until convergence is achieved. It requires numerical solutions with small spatial and time step sizes and significant computation time. Since the implicit scheme used in HMAT deals with nonlinear properties that depend on the moisture and temperature of the material, there is a disadvantage that it takes much computational time for convergence.

3. Steady-State Moisture Flux Model

The simplified model has the advantage of being more convenient for the user than the detailed model but assumes that the movement of moisture in the interior material of the wall or structure is transferred in the form of vapor pressure. Buffering models such as the EMPD assume that the absorption and desorption of moisture moves in a 24 h periodic state. The structure of a building comprises various combinations and depends on the conditions of the exterior or adjacent space. The moisture may pass through the structure and affect the interior spaces. The movement of moisture implies a change in the latent heat release in the structure, which in turn affects the latent heat load in the room.

This paper proposes an SSMF model based on the Glaser method, using its basic equation. The Glaser method evaluates the vapor pressure profile of envelopes, while the SSMF model calculates the vapor flow rate by considering the resistance of vapor flow in the envelopes. In other words, the proposed SSMF model is a simplification in a steady state, to evaluate the latent heat flux according to the movement of moisture. The sensible heat flux and latent heat flux of the structure at steady state can be expressed by the sensible and latent heat resistances of the structure, and the internal and external convective heat resistance and water vapor resistance, respectively. However, it is difficult to represent the heat fluxes (sensible and latent) of walls by using the simplified calculation method, because the sensible and latent heat resistances depend on the temperature and relative humidity in the wall materials. This model has some assumptions. First, the liquid transport in the materials, such as capillary transport and rain wetting, is not included. Second, the water vapor resistance of the materials is assumed to be the average of the moisture in both air conditions.

The steady-state sensible heat flux can be evaluated based on the temperature difference between the outdoor and indoor air and the thermal resistance ($R_{h,Ttl}$, total sensible heat resistance). The steady-state latent heat flux can be calculated based on the vapor pressure difference between the outdoor and indoor air and the moisture resistance ($R_{v,Ttl}$, total latent heat resistance) [17,29]. Therefore, the total sensible heat resistance and total latent heat resistance of the wall are shown in Figure 1, and can be expressed as follows:

$$R_{h,Ttl} = R_{h,ext} + R_{h,in} + \sum_{k=1}^n R_{h,k} \quad (6)$$

$$R_{v,Ttl} = \left(R_{v,ext} + R_{v,in} + \sum_{k=1}^n R_{v,k} \right) \frac{1}{h_v} \quad (7)$$

where $R_{h,k}$ is the thermal conductive resistance in the wall [$\text{m}^2\text{K}/\text{W}$], $R_{h,ext}$ is the outside-surface convective heat resistance [$\text{m}^2\text{K}/\text{W}$], $R_{h,in}$ is the inside-surface convective heat resistance [$\text{m}^2\text{K}/\text{W}$], $R_{v,k}$ is the moisture resistance in the wall [$\text{Pa}\cdot\text{s}\cdot\text{m}^2/\text{kg}$], $R_{v,ext}$ is the outside-surface convective moisture resistance [$\text{Pa}\cdot\text{s}\cdot\text{m}^2/\text{kg}$], $R_{v,in}$ is the inside-surface convective moisture resistance [$\text{Pa}\cdot\text{s}\cdot\text{m}^2/\text{kg}$], n is the number of layers [8], and h_v is the evaporation enthalpy of water [J/kg].

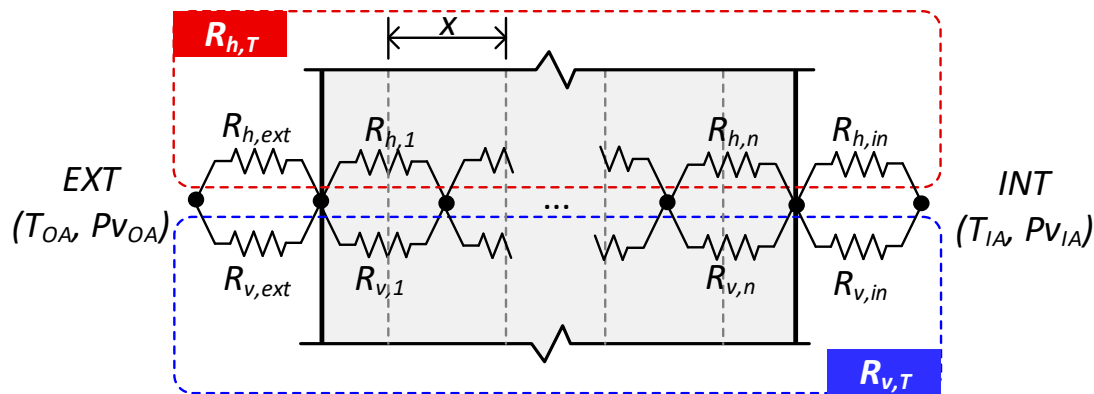


Figure 1. Total sensible and latent heat resistance of the wall (the symbol EXT represents outdoor, and the symbol INT represents indoor).

In Equation (8), the moisture resistance in the wall is calculated from the vapor permeability δ_p and thickness x of the material and the vapor permeability varies with the moisture content of the material. The moisture resistance is expressed as

$$\sum_{k=1}^n R_{v,k} = \left(\frac{x_1}{\delta_{p1}} + \dots + \frac{x_n}{\delta_{pn}} \right) \quad (8)$$

Although the amount of moisture is different for each material, for simplicity the proposed SSMF method assumes that the moisture permeability is used as the average moisture value of indoor and outdoor air that changes over time. The moisture permeability of each material, δ_p , uses the value obtained from the material properties based on the average moisture value that changes over time. Considering the transfer of latent heat through a wall or envelope, using Equation (8) and the difference in vapor pressure, the following equation can be obtained:

$$q_l = \sum_{j=1}^N A_j \frac{\Delta p_v}{R_{v,Tl}} \quad (9)$$

where A_j is the area of the j th surface [m^2], Δp_v is the vapor pressure difference between $p_{v, OA}$ and $p_{v, IA}$, $R_{v,Tl}$ is the total latent heat resistance, and N is the number of surfaces.

Equation (9) can easily solve the latent heat transfer rate by using the difference of vapor pressure and latent heat resistance of the wall. The latent heat transfer through a wall or envelope is applied to the building simulation model in a simpler approach of using steady-state calculations at each time step. The proposed SSMF model can show the effect in the unapplied thermal analysis of latent heat transfer in a wall or envelope. There are many heat transfer models, among which the conduction transfer function (CTF) is, at present, widely used to calculate the conduction heat transfer in building cooling/heating loads and energy calculations [30]. To help understand the SSMF calculation method, we will explain the application of the SSMF model to the CTF model, which is a heat transfer analysis model in Energy Plus. The calculation method is described as follows:

Step 1. Run the CTF-model simulation and output the air temperature, relative humidity, and vapor pressure values of the outdoor and indoor air (living, attic, and room).

Step 2. Calculate the latent heat resistance of materials ($R_{v,Tl}$) with the temperature and relative humidity values of the outdoor air and indoor air at each time step by using Equation (7). Obtain the difference between the outdoor and indoor vapor pressures at each time step (Δp_v).

Step 3. Compute the steady-state latent heat flux at each time step by using Equation (9).

Figure 2 shows the process in which the SSMF model calculates the latent heat transfer value based on the values calculated in EnergyPlus. The latent heat transfer value is

calculated using between the latent heat resistance and the vapor pressure, which is repeatedly calculated for each time step of the calculation.

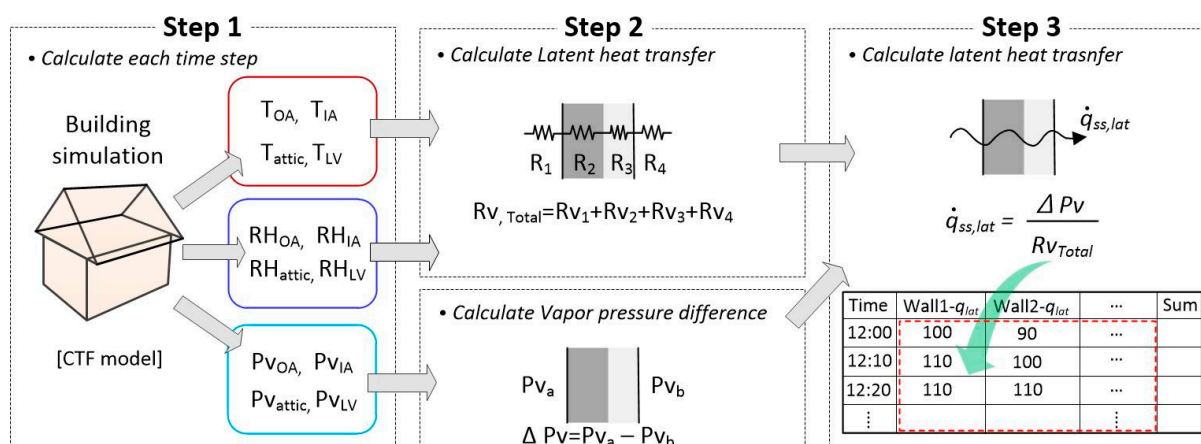


Figure 2. Simulation process of the steady-state moisture flux model for moisture transfer with the model.

4. Evaluation of Alternatives for Heat and Moisture Transfer Model for Residential Buildings

Most building energy simulation tools consider only sensible heat transfer in the building envelope, neglecting the latent (moisture) heat exchange. However, this may lead to inaccurate calculation of the building's thermal load, as well as the cooling and heating energy consumption. Recent research has highlighted the errors in building energy calculations caused by neglecting the moisture exchange effects [2,31–33]. The error is greater if the building is located in a humid region or if the building has many hygrothermal materials, which affect the indoor conditions through the absorption or release of moisture. In addition, with the strengthening of the air-tightness and insulation performance of recently built buildings, the thermal load of the buildings, as well as their heating and cooling system capacity, has significantly decreased. In passive houses or high-performance buildings in a hot and humid region, the sensible heat ratio is reduced from a typical value of 0.8 to 0.6 and the latent heat is relatively increased. Therefore, the calculation of latent heat is more important in highly insulated and air-tightened buildings.

This section aims to explore the opportunities for improved energy modeling using the proposed SSMF model applied to the CTF model, as well as to the EMPD model. The CTF model does not take into account the evaporative heat, which is the latent heat change of the structure due to the vapor pressure change. On the other hand, the EMPD model considers in the latent heat but does not consider the change of moisture on both sides of the envelope, for example, indoors and outdoors. Moreover, both models are less accurate than the detailed heat and moisture transfer model, such as the HAMT model. The SSMF model aims to extend the CTF and EMPD calculations, so that they can better represent the sensible and latent heat transfer calculation of the most accurate method, the HAMT model. The heat and moisture transfer behavior is discussed with the following calculation models: CTF, CTF+SSMF, EMPD, EMPD+SSMF, and HAMT. For the analysis, a residential building under different climate conditions, Miami, Atlanta, and Chicago, is analyzed.

4.1. Simulation Models

For the analysis, the building simulation is performed using EnergyPlus v8.0. The process of the building-envelope thermal load calculation in the EnergyPlus program includes the conduction, convection, and radiation processes of the surfaces inside and outside the building. EnergyPlus offers the option of several alternative methods for heat and moisture exchange, including the CTF model (only sensible heat exchange), EMPD model (simplified heat and moisture exchange), and HAMT model (detailed heat and

moisture exchange). To compare the heat and moisture transfer from the surface of these three models and the models applied to the SSMF model proposed in the CTF and EMPD models, the EnergyPlus simulation program and Matlab program were used. EnergyPlus generates results for three models, and the SSMF model is calculated as an extension of these results for the CTF and EMPD models, and the HAMT model is used as the value to be compared to the other models. Five models, CTF, CTF+SSMF, EMPD, EMPD+SSMF, and HAMT, are compared for the heat and moisture transfer from the building surfaces, as shown in Figure 3 and Table 1.

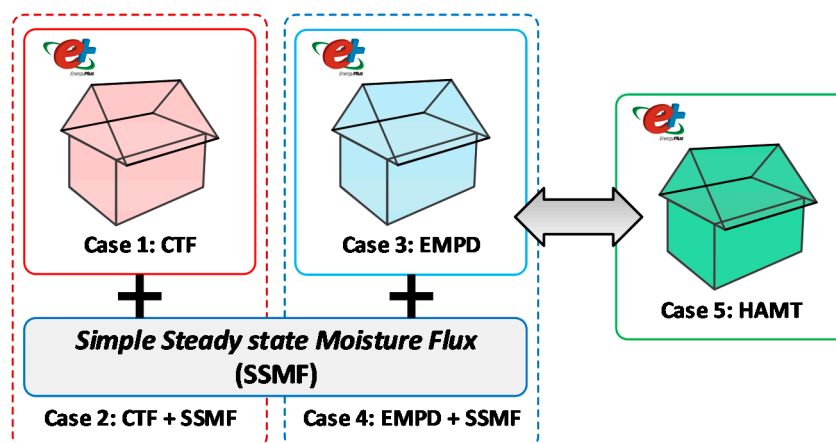


Figure 3. Comparison models.

Table 1. Description of the thermal models in the simulation.

	Model	Description
Case1	CTF	Conduction transfer functions
Case2	CTF+SSMF	Steady-state moisture flux with CTF model
Case3	EMPD	Effective moisture penetration depth with CTF
Case4	EMPD+SSMF	Steady-state moisture flux with EMPD model
Case5	HAMT	Combined heat and moisture transfer

The time step of the simulation was set to 6 min for each model, and those models were calculated by giving a warm-up period of 1 year to stabilize the moisture of the material in the HAMT model. When the calculation was performed with a computer with CPU performance of i7-4770, 3.4 GHz, the simulation runtime is about 700 s for case 1 (CTF model), about 720 s for case 3 (EMPD model), and about 6800 s for case 5 (HAMT model). The CTF model and EMPD model to which the SSMF model (case 2 and case 4) showed the simulation run time of about 1080 s and about 1140 s, respectively. Table 2 shows the average simulation run time for each model.

Table 2. Description of the thermal models in the simulation.

	Model	Simulation Run Time (Seconds)
Case 1	CTF	700
Case 2	CTF+SSMF	1080
Case 3	EMPD	720
Case 4	EMPD+SSMF	1140
Case 5	HAMT	6800

4.2. Simulation Conditions

4.2.1. Climate Conditions

The impact of the latent heat transfer calculated by the SSMF model on the building thermal load is evaluated by a series of simulation analyses. For this evaluation, the weather data for three humid locations (Miami, Atlanta, and Chicago) in the United States are used. Specifically, Miami, FL, is classified as a very hot and humid climate zone; Atlanta, GA, represents a mixed and humid climate zone; and Chicago, IL, is a cool and humid climate zone. The characteristics of the weather in these three locations are listed in Table 3.

Table 3. Locations for the case studies.

Location City	Latitude	Longitude	Degree Days		Annual Average			Climate Zone
			HDD	CDD	Temp (°C)	RH (%)	W (kg/kg')	
Miami, FL	25°46'27" N	80°11'37" W	130	4458	24.5	72.6	0.0143	1A: very hot and humid
Atlanta, GA	33°44'56" N	84°23'16" W	2694	1841	16.6	65.7	0.0090	3A: mixed and humid
Chicago, IL	41°51'00" N	87°39'00" W	6311	842	9.9	70.3	0.0067	5A: cool and humid

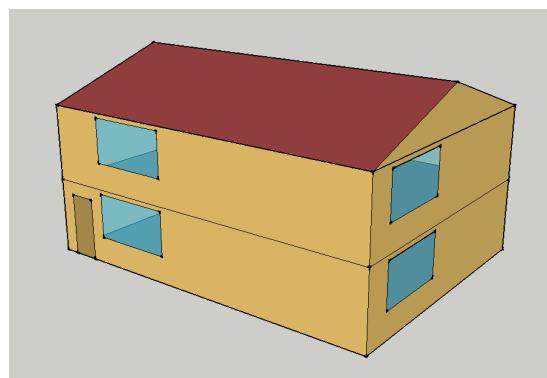
4.2.2. Building Descriptions

The IECC prototype single-family residential building model is used for the simulation analysis [34]. For the prototype building model in different locations, the construction of the building envelope is changed to reflect the building code [35] and construction practices, while other parameters such as building geometry, internal load, window-to-wall ratio, set-point temperature schedule, and HVAC system type remain the same. The moisture properties of the materials used in the simulation are taken from the WUFI material database [23]. Table 4 describes the residential building model used for the analysis.

Table 4. Description of the prototype single-family building model.

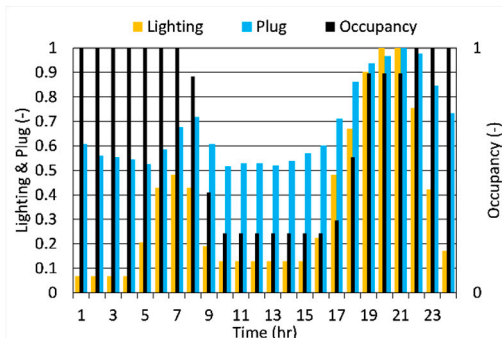
Building type	Residential building (two stories)
Building area	111.53 m ² (1200.55 ft ²)

Building shape



Prototype building.

Table 4. Cont.

Architecture	Exterior wall	Acrylic Stucco + building paper felt + plywood + OSB + fiberglass + dry wall	0.517 W/m ² K (0.091 Btu/h·ft ² ·°F)
	Exterior roof	Plywood + OSB	2.674 W/m ² K (0.471 Btu/h·ft ² ·°F)
	Gable	Acrylic Stucco + building paper felt + plywood + OSB + dry wall	2.727 W/m ² K (0.480 Btu/h·ft ² ·°F)
	Ceiling	Fiberglass + drywall	0.229 W/m ² K (0.040 Btu/h·ft ² ·°F)
	Floor	Plywood + concrete	3.33 W/m ² K (0.586 Btu/h·ft ² ·°F)
	Window	Window fraction: North/South (13.14%) and East/West (15.23%)	2.845 W/m ² K (0.501 Btu/h·ft ² ·°F)
	Infiltration	24 h (effective leakage area method)	600 cm ² (Living) and 370 cm ² (Attic)
	Internal mass	Interior furnishing and lumber truss	9.99 m ² (living) and 35 m ² (Attic)
HVAC	System	Central electric air conditioning and gas furnace	DX cooling coil and gas heating coil
	Thermostat set-point	24 h	23.88 °C (75 °F) Cooling/ 22.22 °C (72 °F) Heating
	Ventilation	24 h	0.151 ACH
Internal loads and schedules	Lighting		1.698 W/m ²
	Plug		2.46 W/m ²
	People		117.28 W/person (3 persons)
	Internal load schedule.		

5. Results

5.1. Very Hot and Humid Climate

To evaluate the impact of moisture transfer by using the SSMF model on surfaces, the daily sensible and latent heat transfers are compared. The comparison in this study is conducted with other models based on the HAMT model and verified by two benchmark tests: HAMSTAD benchmark [36,37] and EN 15026 benchmark [38] tests.

The daily heat transfer of surfaces in Miami during July is shown in Figure 4. Figure 4a shows the sensible heat from all inside surfaces and the internal surface temperature of the south wall. The CTF model exhibits the largest fluctuation of the inside surface temperature, while the HAMT model exhibits the smallest fluctuation. This is attributable to the moisture contents of the building materials. When the building materials contain moisture, their effective heat capacity increases, and therefore, the fluctuation of the inside surface temperature of the materials reduces. Less fluctuation of the inside surface temperature leads to a gradual change in the indoor air temperature. As a result of the surface temperature of each model, the change in sensible heat shows the same pattern. The CTF model has the largest fluctuation, while the HAMT model has the smallest fluctuation. Figure 4b shows the latent heat transfer in each model. The daily latent heat transfer of the

CTF+SSMF model is much higher than that of the remaining models, because of the vapor flow from the attic to the living space. The CTF+SSMF model indicates that the amount of moisture flow through the ceiling is overestimated, which is attributed to the fact the CTF model does not consider the moisture absorption and desorption effect. The daily latent heat transfer of the EMPD+SSMF model is similar to that of the HAMT model. Figure 4c shows the daily total heat transfer of all surfaces in each model. Among all models, the EMPD+SSMF model produces the closest result to the HAMT model.

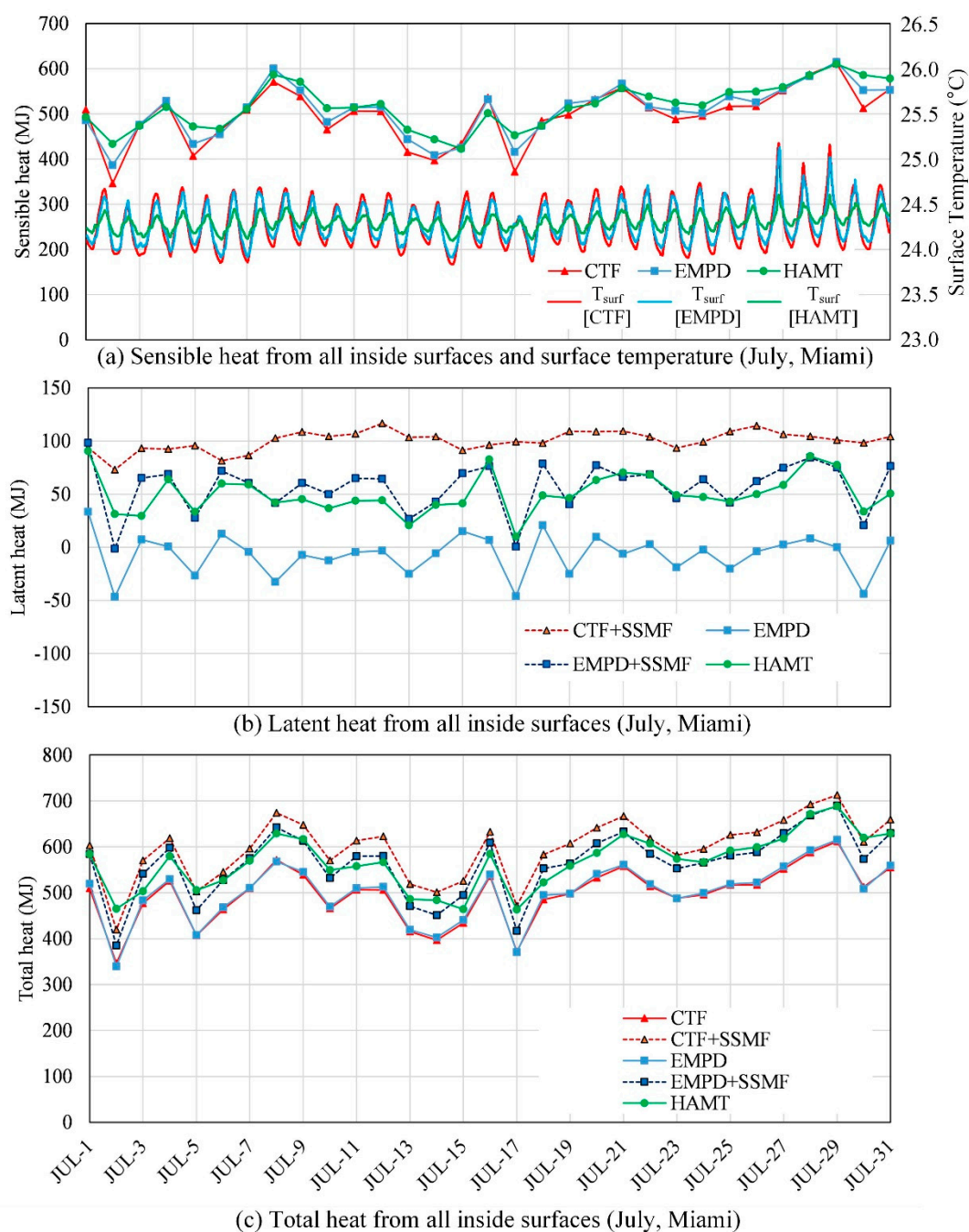


Figure 4. Daily heat transfer of all surfaces in Miami (July): (a) sensible heat transfer from all inside surfaces and surface temperature, (b) latent heat transfer from all inside surfaces, and (c) total heat transfer from all inside surfaces.

The monthly total heat transfer of all surfaces in the building, with each model, and the difference error compared to the HAMT model are shown in Figure 5. The calculation

of the difference error uses the mean absolute percentage error. The difference error is expressed as the mean absolute percentage error (MAPE) between the heat transfer value of the HAMT model and that of each model. MAPE is presented in Equation (10).

$$MAPE = \frac{1}{n} \sum_{i=1}^N \left| \frac{A(i) - F(i)}{A(i)} \right| \quad (10)$$

Here, $A(i)$ is the results of HAMT and $F(i)$ is the result of other models.

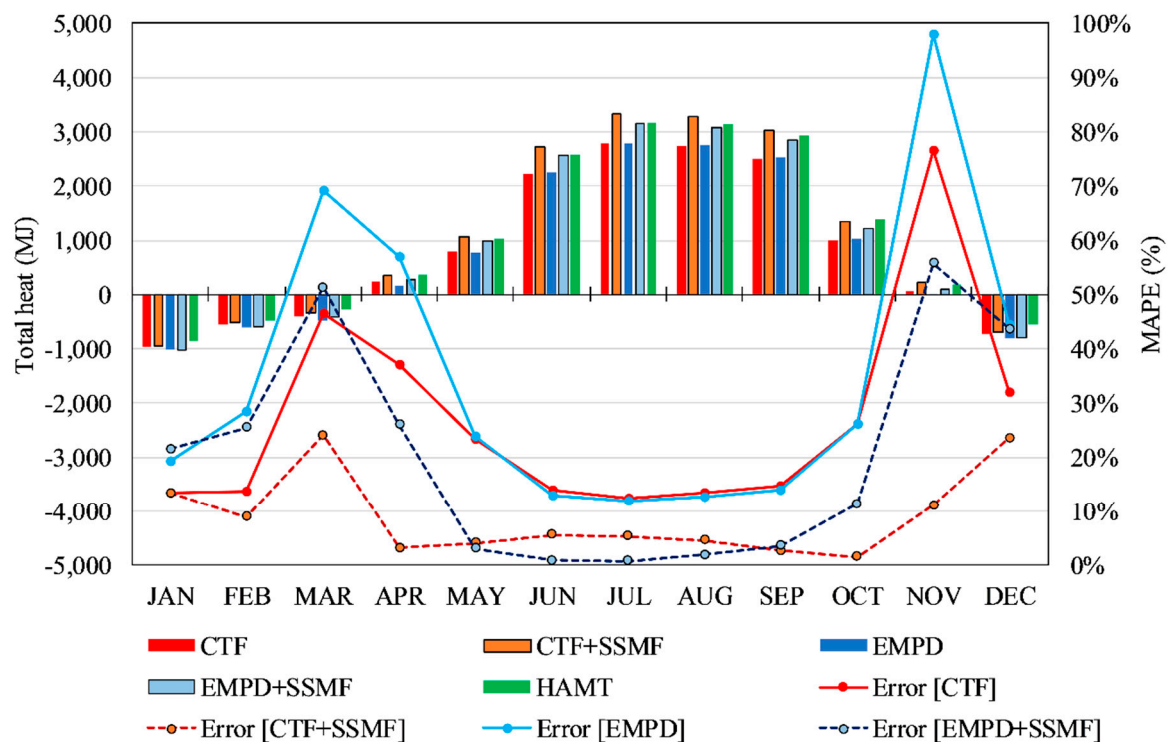


Figure 5. Monthly total heat transfer from surfaces and the monthly percentage difference between models in Miami.

The positive value of the bar graph indicates that the heat flows from the outside to the inside of the building, while the negative value indicates that the heat flows from inside to outside. When the SSMF model is applied, the deviation in the CTF and EMPD models is reduced from February to November. The deviation between the HAMT model and the EMPD+SSMF model is less than 5% between May and September. Applying the SSMF model to the CTF and EMPD models reduces the annual total heat transfer errors of the CTF and EMPD models by 22% and 16%, respectively.

5.2. Mixed and Humid Climate

The daily heat transfer of surfaces in Atlanta during July is shown in Figure 6. The daily sensible heat transfer of all surfaces and the inside surface temperature are similar in Figure 6a. Similarly to the observation in Miami, as shown in Figure 6b, the daily latent heat transfer of the CTF+SSMF model is higher than that of the remaining models. The daily latent heat transfer of the EMPD+SSMF model is similar to that of the HAMT model. When the SSMF model is applied to the EMPD model, the error between the EMPD and HAMT models is reduced. Especially, it shows a significant effect on error reduction in moisture transfer through the ceiling, as shown in the results for Miami. Figure 6c shows the daily total heat transfer of all surfaces in each model. Among all models, the EMPD+SSMF model produces the closest result to those of the HAMT model.

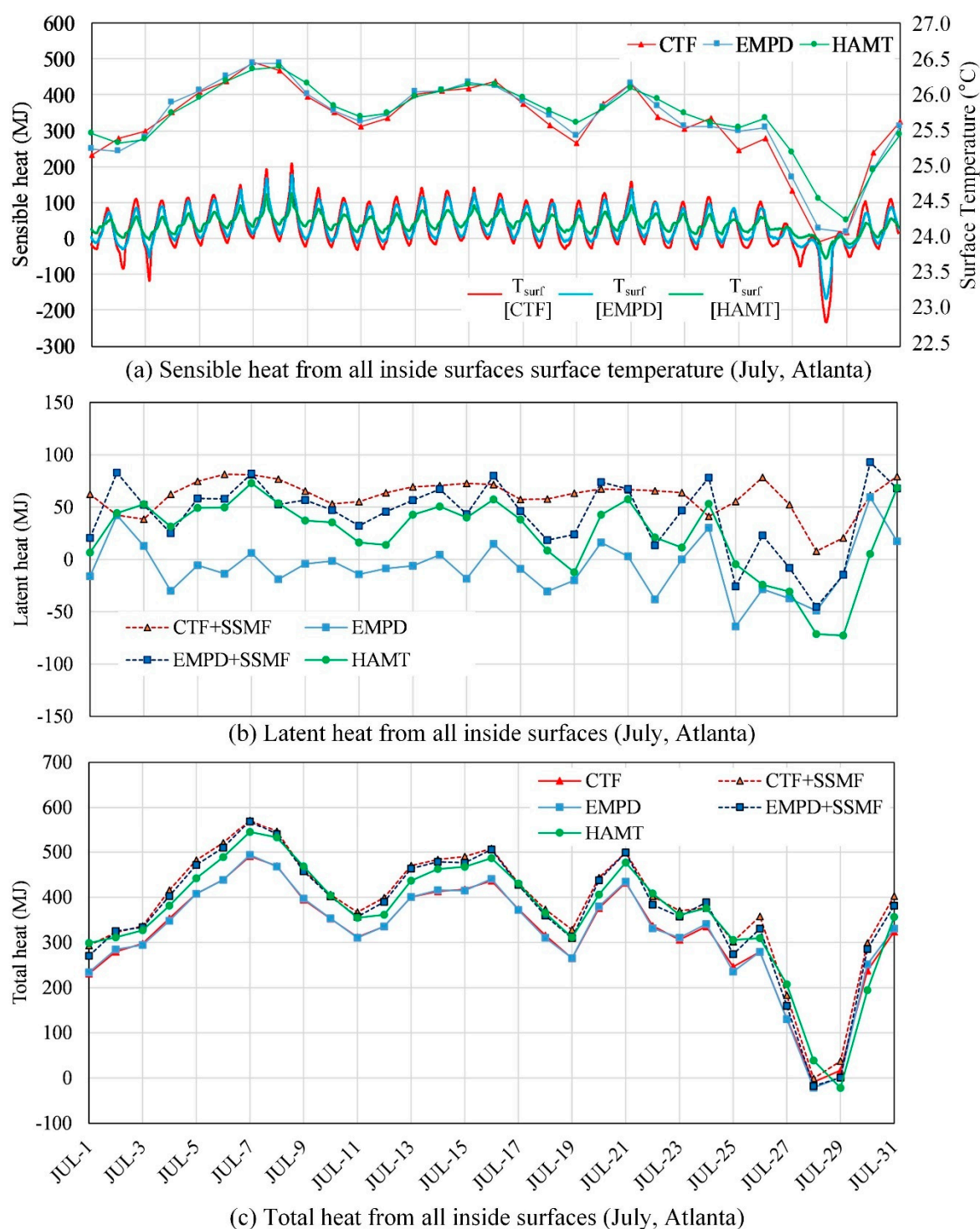


Figure 6. Daily heat transfer of all surfaces in Atlanta (July): (a) sensible heat transfer from all inside surfaces and surface temperature, (b) latent heat transfer from all inside surfaces, and (c) total heat transfer from all inside surfaces.

The monthly total heat transfer of all surfaces in building with each model is shown in Figure 7. The deviation in the CTF and EMPD models is reduced from June to September. These months show a decrease in the deviation in the latent heat transfer. The deviations for the EMPD+SSMF model are less than 5% from May to August. However, unlike the results for Miami, from October to April, there is little or no error in the applied SSMF model because the inside moisture is larger than the outside moisture and the difference in

moisture is small. Applying the SSMF model to the CTF and EMPD models reduces their annual total heat transfer errors by 7% and 6%, respectively.

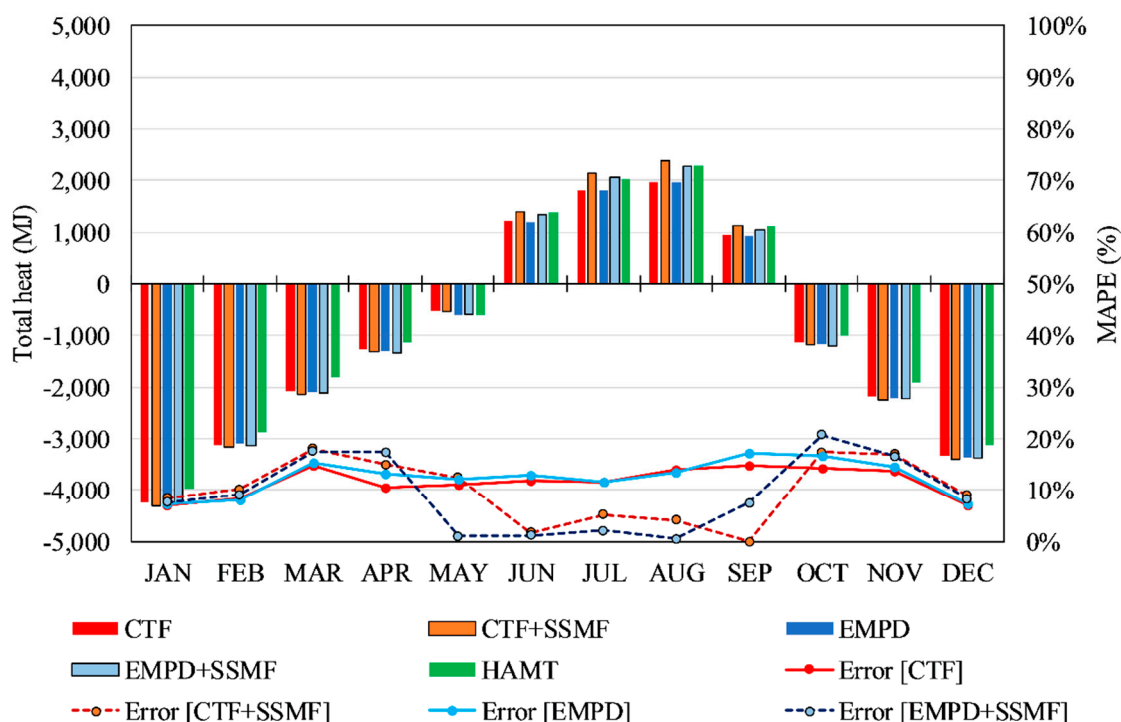


Figure 7. Monthly total heat transfer from surfaces and the monthly percentage difference between models in Atlanta.

5.3. Cool and Humid Climate

The daily heat transfer through all structures in Chicago during July is shown in Figure 8. The daily sensible heat transfer of all surfaces is similar, as shown in Figure 8a. In Figure 8b, the daily latent heat transfer through all surfaces in the EMPD+SSMF model is similar to that in the HAMT model. When the SSMF model is applied to the EMPD model, the error between the EMPD and HAMT models is reduced. Figure 8c shows the daily total heat transfer through all surfaces in each model. Among all models, the results of the EMPD+SSMF model are closest to those of the HAMT model.

The monthly total heat transfer of all surfaces in the building with each model is shown in Figure 9. When the cooling is mainly required from June to September, the deviation for the EMPD+SSMF model reduces the error. The deviation between the HAMT and EMPD+SSMF models is less than 5% in July and August. In the heat-dominated months, when the SSMF model is applied, there is little or no error increase because the sensible heat transfer takes up the major part in total heat transfer. Applying the SSMF model to the CTF and EMPD models reduces the annual total heat transfer errors of the CTF and EMPD models by 0.5% and 0.7%, respectively.

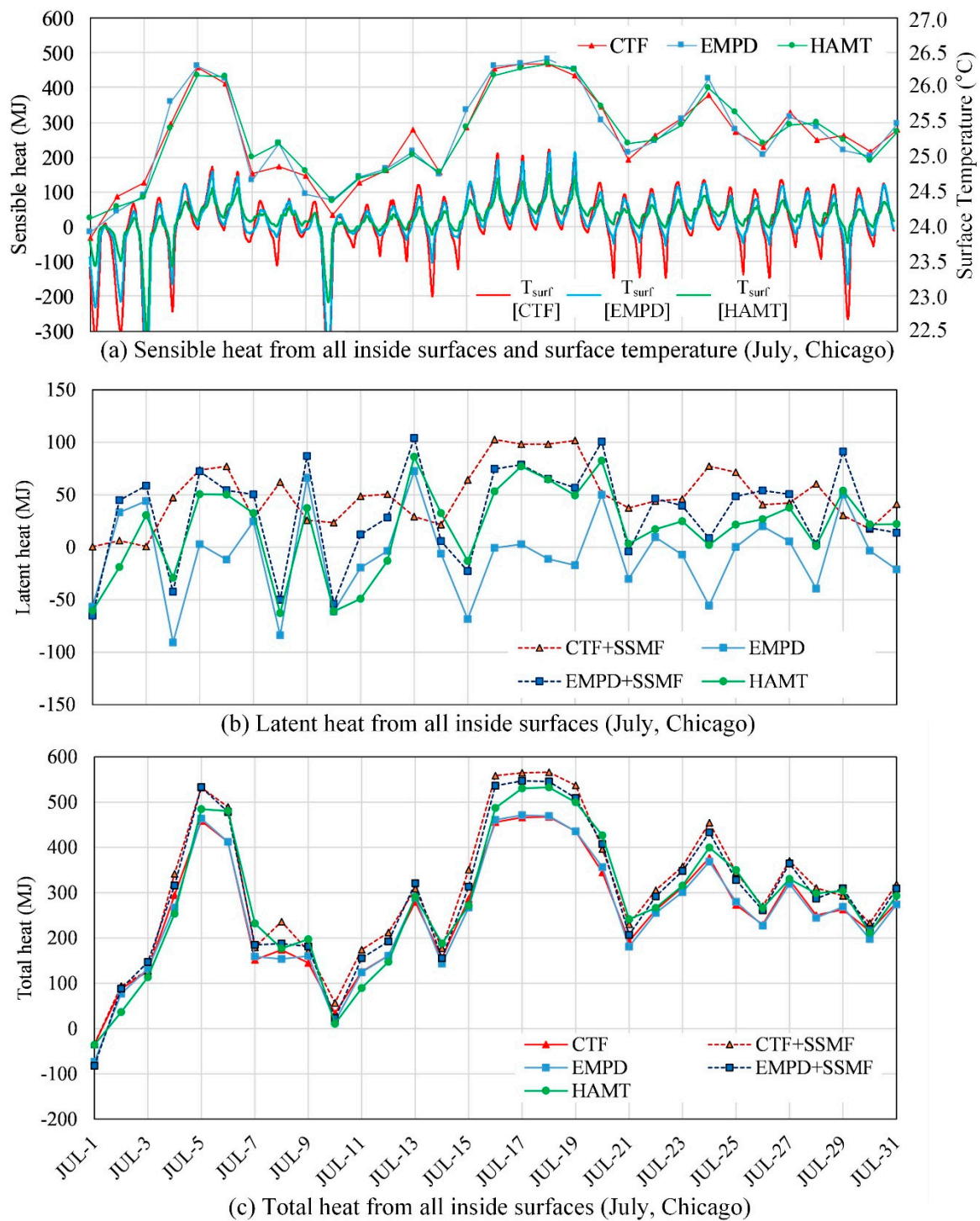


Figure 8. Daily heat transfer of all surfaces in Chicago (July): (a) sensible heat transfer from all inside surfaces and surface temperature, (b) latent heat transfer from all inside surfaces, and (c) total heat transfer from all inside surfaces.

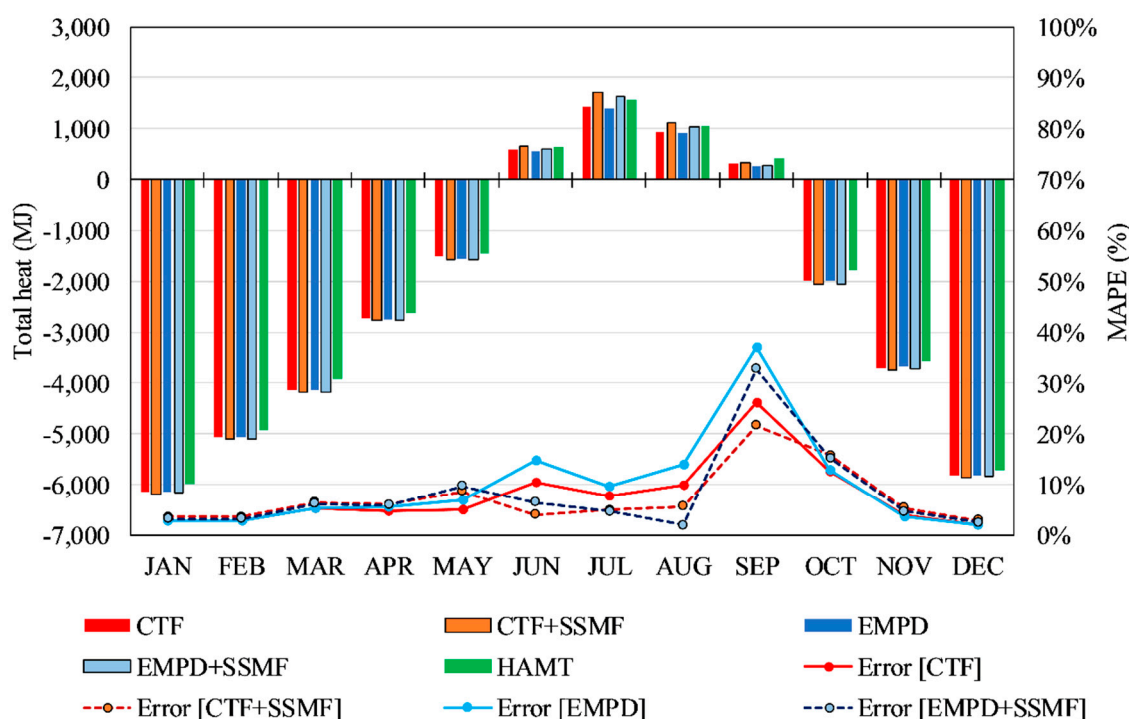


Figure 9. Monthly total heat transfer from surfaces and the monthly percentage difference between models in Chicago.

Applying the SSMF model to the CTF and EMPD models shows less heat transfer error than the current models. Especially, the error reduction is dominated in the ceiling where the latent heat flows between the attic and living space. The prediction errors for the CTF+SSMF model can be largely attributed to inaccurate modeling of the attic vapor pressure because the moisture absorption/desorption in the inside materials of the envelope and interior surfaces is not considered. When the SSMF model is applied the EMPD model, the prediction error is largely reduced as compared to the case of the unapplied EMPD model.

In particular, the SSMF model provides the best prediction accuracy during cooling in hot and humid climates when the outdoor humidity ratio is consistently above the indoor humidity levels. Under these conditions, the moisture flux through the ceiling can impose a significant additional latent cooling load. However, the results for Atlanta and Chicago have fewer clear effects. In these locations with greater heating than cooling, applying the SSMF model does not show a significant effect. During the period in which heating is required, the moisture difference between indoor and outdoor is relatively small compared to the cooling period. As a result, the amount of latent heat is relatively small compared to that of sensible heat. In the application of the model, the error is reduced when the SSMF model is applied to the EMPD model rather than the CTF model. This is because the EMPD model is calculated considering moisture storage and moisture absorption/desorption, and the vapor flow through the envelopes is considered due to the SSMF model.

6. Conclusions

This study aimed to explore the behavior of heat and moisture transport in building envelopes and to develop and test simplified heat and moisture transfer methods for use in residential building energy modeling tools. In the previous study and in this study, the results of combined heat and moisture transfer were different from those of heat transfer alone. Changes in sensible heat, and in particular, latent heat due to the movement of moisture should be considered in predicting accurate internal conditions. A simple steady-state moisture flux method was developed for improving the CTF and EMPD models. The SSMF model is a calculation method that considers the movement of moisture through the

envelope and can be easily calculated from the moisture transfer resistance of the envelope and the amount of moisture inside and outside the building.

Case studies for building performance with different heat and moisture transfer models were performed to investigate the contribution of the proposed SSMF method. Five models, CTF, CTF+SSMF, EMPD, EMPD+SSMF, and HAMT, were compared for the heat and moisture transfer from building surfaces. A prototype residential building was analyzed in three cities, Miami (very hot-humid), Atlanta (mixed-humid), and Chicago (cool-humid). The following results were obtained.

- (1) In Miami, from May to September, the percent difference between the HAMT model and the EMPD+SSMF model was less than 5%. As for the deviation of annual total heat transfer between the HAMT model and the analyzed model, the CTF model coupled with the SSMF model reduced the deviation in the annual total heat transfer from -24% to 2% , compared to the CTF model alone. The SSMF model also decreased the error of the EMPD model from -26% to -10% ; cooling coil loads were also reduced.
- (2) In Atlanta, the monthly deviations between the HAMT model and the EMPD+SSMF model were the lowest, at 5%, among the analyzed cases. For the CTF model, when coupled with the SSMF model, the deviation in the positive annual total heat transfer decreased from -13% to 3% and that in the negative annual total heat transfer increased from 9 to 11%. For the EMPD model, the error of the positive value was cut down from -13% to -1% by applying the SSMF model, while that of the negative value increased from 10% to 11% by applying the SSMF model.
- (3) In Chicago, compared to the monthly total heat transfer calculated by the HAMT model, the SSMF model effectively reduced the errors of the CTF and EMPD models during June to September. The deviation between the HAMT model and the EMPD+SSMF model was less than $\pm 5\%$ in July and August. However, the SSMF model actually increased the error in the overall cooling coil load.

The results suggest that the effect of the SSMF model is limited during the heat-dominated periods. First reason is that the humidity difference between the outdoor and indoor environments is relatively small compared to the cooling-dominated periods. Second reason is that the latent heat calculated by the SSMF model is small and does not have much significant effect. In heat-dominated periods, the amount of latent heat transfer through the surface of the HAMT model was very small, about 0.1% to 1% of the total heat transfer. On the other hand, for the cooling-dominated periods, the applied SSMF model is effective at reducing the error between the conventional models and the reference heat and mass transfer model, especially in hot and humid climates. For Miami, under the application of the SSMF model, modeling errors of monthly surface heat flux are reduced by up to a factor of 10.

In the results, the model that applied SSMF to the EMPD model showed the biggest reduction in the error with HAMT. This seems to be the result of considering the movement of moisture in consideration of the moisture buffer and moisture passing through the structure. In particular, the movement of moisture in the ceiling between the attic space and the living space was carefully considered. In general, it seems that external environmental factors influence the change of moisture, and the characteristics of the attic space with many wood masses where moisture is well stored and discharged are well reflected in the SSMF model.

In this study, the proposed SSMF model has many limitations compared to the detailed heat and moisture model. However, as the accuracy increases compared to the heat transfer model or simple heat and moisture transfer model used in the calculation of cooling loads, it is believed that more accurate predictions can be made.

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