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Computer simulation of pedestrian's transient thermal comfort in a complex urban context: a bottom-up modeling approach

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Abstract
This study aims to take a bottom-up modeling approach to simulate pedestrian's transient and dynamic thermoregulatory condition while walking in the complex outdoor urban environment. Effective assessment of pedestrian's thermal comfort is a complicated issue and traditional steady-state bio-meteorological indices such as PMV have been shown to be unsuitable for this task. A dynamic simulation model that allows pedestrian's adaptation to the varying local microclimate to be examined is expected to provide a solution to this problem. The present study adopts a bottom-up modeling paradigm and uses a promising modeling technique, the agent-based modeling approach, to simulate each individual pedestrian's movement behavior and thermal comfort condition. A modified two-node model is implemented to assess pedestrian's thermoregulation. The simulation system is implemented with a geographical information system (GIS) framework, allowing a complex urban context and the corresponding urban microclimate to be modeled. Based on the simulation, both spatial and temporal analyses can be conducted. A case study is carried out to demonstrate how the system can be effectively applied in the real world.

Keywords
Pedestrian thermal comfort, two-node model, thermal transient, agent-based modeling,

1. Introduction

Cities are becoming hotter today. The global trend of temperature rise, commonly known as "global warming" has been well documented in IPCC's (Intergovernmental Panel on Climate Change) report (IPCC, 2007). At the same time, the rapid urbanization process the whole world is experiencing (UNFPA, 2007) results in the widely observed urban heat island (UHI) effect. In such a global context, cities especially those in adverse climates suffer from heat stress and are particularly vulnerable to extreme weather condition such as heat wave. Morality occurs in the worst case (Leung, Yip, & Yeung, 2008; Nastos & Matzarakis, 2011). Therefore how to mitigate citizen's thermal stress and improve thermal comfort has been a continuous endeavor in town planning.

The assessment of the thermal comfort condition of pedestrians outdoors is a twofold challenge. Firstly, outdoor urban environment is always complex and non-uniform, e.g., irregular building form, variation of sunshine and shade. Secondly, people outdoors are dynamic and always in a non-steady state (Höppe, 2002), which makes the laboratory-based steady state assessment schemes not suitable. Although some physical measurement protocols have been proposed for monitoring pedestrians' thermal transient (Potvin, 2004), the extensive equipment requirement imposes great limitation when applied in practice.

This paper proposes a computational approach to model the urban microclimate and assess pedestrian thermal comfort in the "virtual" sense. With the help of the geographical information system (GIS), complex urban form and microclimatic conditions can be modeled. A bottom-up simulation approach, the agent-base modeling (ABM) is presented to model each individual pedestrian's thermal transient condition as she walks in the urban environment.

2. Background

The most commonly adapted method for outdoor thermal comfort assessment is bio-meteorological indices which describe human thermal comfort by linking local microclimatic condition with human thermal sensation. The underlying assumption is that a human subject has reached her thermal equilibrium in such an ambient microclimate, and the indices characterize the object's steady-state thermal conditions. Notable examples include the ISO-standardized Predicted Mean Vote (PMV) (Fanger, 1982; ISO, 1994) which is one of the most widely applied thermal comfort indices, and the temperature-scaled Physiological Equivalent Temperature (PET) (Höppe, 1999; Mayer & Höppe, 1987), etc. There are also other indices such as the OUT-SET* (Pickup & De Dear, 1999) and the Universal Thermal Climate Index (UTCI) (Jendritzky, Maarouf, & Staiger, 2001) which are less influential.

A problem with the aforementioned steady-state indices when applying in outdoor thermal comfort studies is that pedestrians are seldom in their steady state, as walking involves transient process and dynamic and temporal thermal adaptation. In such a case, the use of steady state indices will normally cause problems in assessing pedestrians' "actual" thermal sensation. Indeed Höppe (2002) has explicitly shown the difference between a pedestrian's dynamic thermal adaptation and the theoretical steady state condition using a simple "sunny street segment" case.

Increasing concerns have been raised to develop methods for assessing human dynamic thermal adaptation in an unsteady-state (Nagano & Horikoshi, 2011; Shimazaki, et al., 2011; Zolfaghari & Maerefat, 2010). Most methods are based on the Pierce Two-Node Model (TNM) (Gagge, Stolwijk, & Nishi, 1971). As the name implies, this model treats the human body as two isothermal parts, skin and core, based on which the thermoregulation, i.e., heat exchange equations are constructed for the passive state. Effectively, core temperature, skin temperature and mean body temperature can all be derived by their deviation from the set points. Other thermoregulatory indicators such as sweating rate and skin blood flow can also be evidently defined. Notably today's commonly used TNMs are based on a substantial update of the initial model (Gagge, Fobelets, & Berglund, 1986). The model has been continually expanded, such as considering the impact of the wind environment (Parsons, Havenith, Holmér, Nilsson, & Malchaire, 1999), implementation of 3-D representation of human body to respond to complex urban environment (Huizenga, Zhang, & Arens, 2001), introducing additional parameters of individual properties such as body composition or acclimatization status (Havenith, 2001), and expanding the two-node model to multi-node models representing different body parts (Foda & Sirén, 2010). In the present study, TNM is selected as the tool for assessing pedestrian's thermal transient condition.

3. Methodology

In this section, a computational approach is presented which models the urban microclimate and assesses pedestrian thermal comfort in the "virtual" sense. A computer simulation system is implemented to model each individual pedestrian's movement in the urban environment and thermal transient from bottom-up. In contrast with the traditional top-down modeling paradigms, this individual-based modeling approach, commonly named as *agent-based modeling*, characterizes a system by looking at its constitutional units – the agents. This promising modeling technique is particularly suitable for the objective of this study in that it allows detailed examination of a person by connecting her thermal transient condition with the local microclimatic condition. The idea of agent-based modeling of pedestrian's thermal comfort is largely inspired by the BOTworld system by (Bruse, 2007). However the major conceptual difference is that, in the present system, a person agent behaves and is analyzed in a real world -like complex urban context as opposed to the rasterized grid space in BOTworld. The system defines the immediate climatic environment the pedestrian is exposed to, including air temperature, wind speed, solar radiation, etc. The pedestrian's personal properties, such as body weight and walking speed, are also defined or generated in the system. The software structure of the system is shown in Figure 1. The implementation of the TNM is presented in the next section.

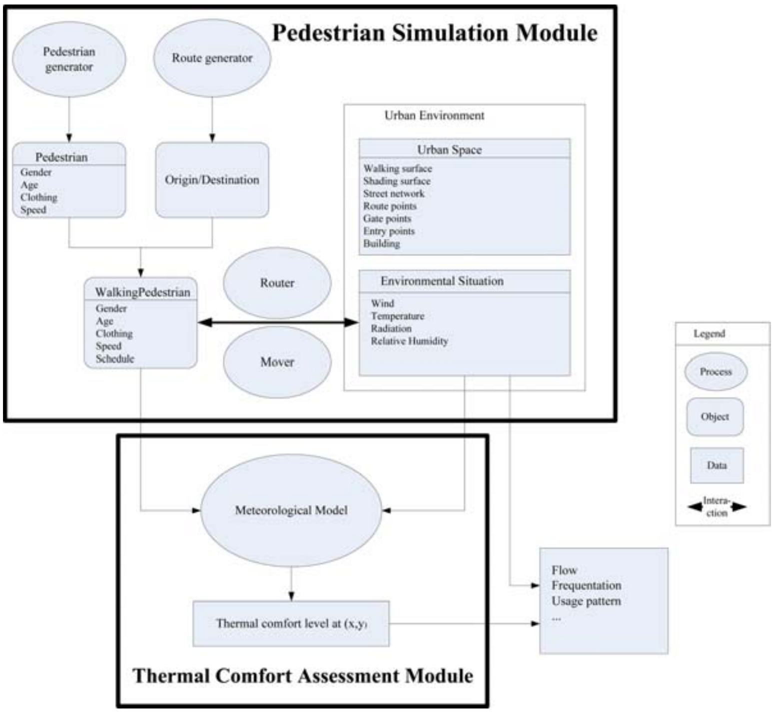

Figure 1: Software structure of the computational system.

The computer program written in C++ programming language published in (Fountain & Huizenga, 1995) is used in this study. The program is rewritten in Java programming language and implemented as an object of a person agent. The model is modified to account for the wind environment based on (Parsons, et al., 1999). Notably the biggest change made to the original program is that a "temporal" characteristic is added: the model is integrated with the movement control of a person agent, allowing the temporal update along with the agent's spatial variation. Due to page limitation, only main formulas are presented here.

In the implemented TNM, two coupled heat balance equations are used to govern transient energy balance (Eq. 1 & 2).

$$S_{core} = M - W - (Q_{c,res} + Q_{e,res}) - Q_{cr->sk} \quad (1)$$

$$S_{skin} = Q_{cr->sk} - (Q_c + Q_r + Q_e) \quad (2)$$

where

S_{core} is heat storage rate in core;
M is metabolic rate;
W is work;
$Q_{c,res} + Q_{e,res}$ is the total respiratory heat loss (convective and evaporative);
$Q_{cr\text{->}sk}$ is the heat flow from core to skin;
$Q_{sk\text{->}cr}$ is the heat flow from skin to core;
S_{skin} is the heat storage rate in skin;
$Q_c + Q_r + Q_e$ is the total evaporative heat loss at skin surface (convective, radiative, and sweating).

The net radiant heat loss from the body surface as determined by clothing is governed by

$$\mathrm{RS} = f_{frac} \cdot f_{acl} \cdot \sigma \cdot \varepsilon \cdot ((T_{cl} + 273.15)^4 - (T_{mrt} + 273.15)^4)) \qquad (3)$$

where
f_{frac} is the fractional body surface area exposed to the thermal environment, and the value of 0.725 is suggested by (Fanger, 1982) for a standing person;
f_{acl} is the increase in body surface due to clothing, and a correction is made considering the walking effect of a person on the intrinsic clothing insulation I_{cl} using the equation proposed by (Havenith, Holmér, & Parsons, 2002);
σ is the Stefan-Boltzman constant, value is $5.67 \cdot 10^{-8}$ W/m^{2}K^4;
ε is the skin emissivity, estimated as 0.98;
T_{cl} is the clothing temperature;
and T_{mrt} is the mean radiant temperature. T_{mrt} is a very important factor in determining the energy balance of a human object, and various methods have been used to estimate it (Thorsson, Lindberg, Holmer, & Eliasson, 2007). In the present methodology the SOLWEIG system (Lindberg, Holmer, & Thorsson, 2008) is used to calculate T_{mrt} for an entire domain.

The model calculates T_{cl} in a iterative manner. At each iteration step, T_{cl} is estimated by:

$$T_{cl} = (T_{skin} / I_{cl} + f_{acl} \cdot (h_c \cdot T_a + h_r \cdot T_{mrt})) / (1 / I_{cl} + f_{acl} \cdot (h_c + h_r)) \qquad (4)$$

where
T_a is the air temperature;
h_c is the convention heat transfer coefficient;
h_r is the radiant heat transfer coefficient.
In this way, transient T_{skin}, T_{core}, and other thermoregulatory parameters can be calculated by their temporal deviation from the set points. In the model, an updating time interval ranging from 1 sec to 1 min can be selected.

Notably, the relative wind speed a walking person experiences is calculated by

$$\overrightarrow{V^{r}_{wind}} = \overrightarrow{V_{wind}} - \overrightarrow{V_{walk}} \qquad (5)$$

where $\overrightarrow{V_{wind}}$ is the actual wind velocity, $\overrightarrow{V_{walk}}$ is the person's walking velocity.

Some input parameters also need to be selected properly. A human object is set to have a T_{skin} of 33.7°C and a T_{core} of 36.8°C, as the neutral state of human body. Similar setting is also selected by (Höppe, 2002). The person's metabolic rate, measured in the unit of MET (the Metabolic Equivalent of Task), is estimated to be 3 METs considering the normally walking speed of 1m/s to 1.5m/s according to (Ainsworth, et al., 2000).

The implemented TNM is verified with The *WWW Thermal Comfort Index Calculator* by de Dear (N/A). A simple urban climatic condition is defined: the air temperature T_a is set to be 30°C, and the Mean Radiant Temperature (T_{mrt}) is set to be 42°C, and the relative humidity is set to be 50%. The default setting for the subject used by the WWW Calculator is selected, which is 70.0kg weight, 0.6 clo clothing insulation, and 58.2W/m^2 metabolic rate. A temporal course of 60 min exposure time is calculated. The option of *Transient Values* is selected, meaning that the subject's thermal condition for each minute is calculated. Meanwhile, same values are calculated using the implemented TNM model. In practice, this is easily done by assigning a "virtual walk" for a person agent. The walk is set to have a length of 60 steps, with each step representing 1 minute's course. The person agent's thermal condition is therefore updated for each step. Values calculated include skin temperature (T_{skin}), core temperature (T_{core}), respiratory evaporative heat loss (E_{res}), respiratory sensible heat loss (C_{res}), dry heat loss from skin surface (DRY), total evaporative heat loss at skin surface (ESK), and skin blood flow (SKBF). There are other values that are possible to be calculated, nevertheless they can all be derived based on the above mentioned parameters, so for the purpose of the verification, these 7 values should be enough for comparison with the WWW Calculator. For E_{res} and C_{res}, both methods give the same results, being two constant values during the temporal course, which are 3.76 (W/m^2) and 0.326 (W/m^2) respectively. The comparisons of the other values which vary temporally are plotted. Due to the page limitation, only the case for T_{skin} is shown (Figure 2). Other parameters show similar results.

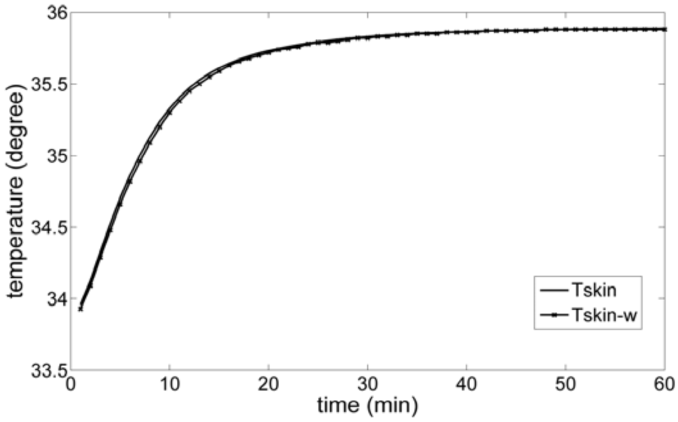

Figure 2: Temporal Comparison between TNM and WWW Calculator: skin temperature (T_{skin}). The value calculated by TNM is denoted as T_{skin}, and the value calculated by the WWW Calculator is denoted as $T_{skin\text{-}w}$.

4. Results and discussions

A real-world case study is presented to show the effectiveness of the dynamic assessment and the applicability of the computational system. A densely built-up downtown area is selected as the study site. Differences in building height and density are commonly found in the domain. The thermal assessment concerns a summer afternoon case. The meteorological condition of the simulated day is summarized in Table 2.

Table 2: Summary of meteorological condition of the simulated day.

Date	Modeling period	T (°C)	Radiation (W/m2)	RH (%)	Sunshine (hour)
9, May, 2008	14:00-15:00	30	500	65	10.5

A simple short-distance walking scenario is simulated to illustrate the idea of monitoring the thermal transient process of a single person while he/she walks in the urban environment. The origin point, destination point and path of the walking are shown in Figure 3. The path is about 130 m long with various shading and sunny conditions. Therefore, diverse thermal comfort conditions of the person are expected to be observed. A “standard object” (male, 40 yrs, 1.75 m, 75 kg, 1.2 m/s walking speed) is selected and monitored. The subject is initially set to have a core temperature (T_{core}) of 36.8 °C, and a skin temperature (T_{skin}) of 33.7 °C, as the neutral state. Detailed temporal physiological condition variation of the subject is shown in Figure 4. In parallel, the subject’s steady state is also calculated, including his steady state core temperature ($T_{core\text{-}st}$) and steady state skin temperature ($T_{skin\text{-}st}$). The subject's local radiation, as describe by the Mean Radiant Temperature (T_{mrt}) and his PET value are calculated based on the local meteorological condition and shown for reference.

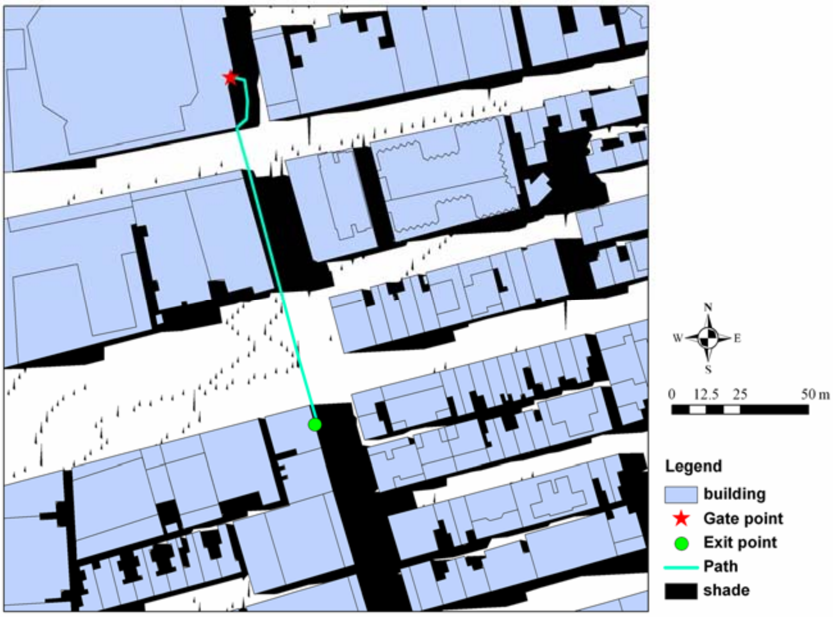

Figure 3: Map showing the origin, destination and path of the walking scenario. The origin point is represented by a red star. The destination point is represented by a green dot. The path is represented by light blue color.

Figure 4: Temporal variation of a walking agent's thermal comfort state, described by skin temperature (T_{skin}) and core temperature (T_{core}). The subject's steady state

condition is also calculated, including his steady state core temperature ($T_{core-st}$) and steady state skin temperature ($T_{skin-st}$). Tmrt and PET are also shown for reference.

As shown in Figure 4, during the 120 second walking in the urban environment, the pedestrian's thermal stress is quite high, with T_{skin} increasing from 33.7 °C to 34.8 °C, which is still substantially lower than the steady state ($T_{skin-st}$) of ~35.5°C under the given climatic condition. Under shaded area, the pace of the increase is relatively lower, as illustrated by the course from 40 s to 80 s where the temperature changing rate is 9.44×10^{-3} °C/s; whereas under insolation, the pace is higher, as the courses from 20 s to 40 s, and 80 s to 100 s, with temperature changing rate being 1.02×10^{-2} °C/s and 1.22×10^{-2} °C/s, respectively. This changing rate difference is consistent with the spatial variation of T_{mrt}. On the other hand, T_{core} shows a much slower changing rate, which is only increased by 0.18 °C after the walking and is constantly 0.2 to 0.3 °C lower than the steady state. This suggests that under hot condition, the core part of human body has a much slower adaptation rate compared with the skin part. The simulation result also clearly shows that the thermal adaptation process of a pedestrian is dynamic, and the pedestrian is constantly in an un-steady state, therefore steady-state models are not suitable in this case. This conclusion also confirms the findings by Höppe (2002).

In order to have an overall picture of the selected subject's thermal load, his temporal energy balance condition is calculated and plotted, as is shown in Figure 5. The effect of the local microclimate, predominantly radiation, on the overall energy balance of the walking pedestrian can be well observed from the figure. The pedestrian has a constantly positive energy balance in the order of 290 W/m^2 to 200 W/m^2, especially under sun exposure. This indicates that, during the walk, the pedestrian is in an unsteady state, and the body keeps "heating up".

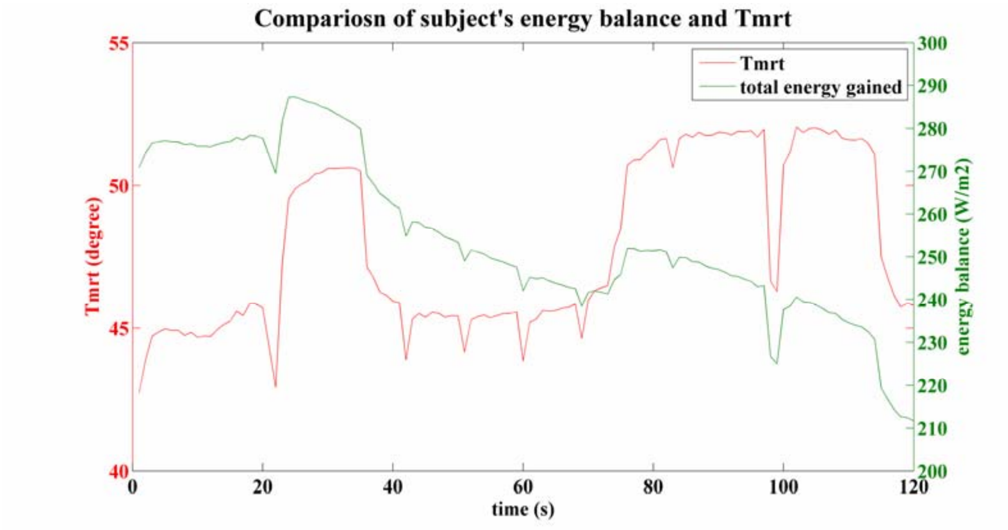

Figure 5: Temporal course of a walking agent's energy balance condition (W/m^2) compared with the local T_{mrt}.

5. Conclusions

This paper establishes a bottom-up computational framework to model pedestrian's thermal transient process. A modified Two-Node Model is implemented to assess pedestrian's thermal comfort condition. A case study in the real world is carried out to show how the system can assess pedestrian thermal comfort in a complex urban environment. The case study confirms that steady-state models are not suitable for assessing pedestrian's dynamic thermal adaptation. The system is shown to be an appropriate tool in accounting for pedestrian's individualized and dynamic characteristics in evaluating their thermal transient condition. How the GIS support allows complex urban environment to be modeled effectively is also demonstrated.

The case study are rather at a preliminary stage. In terms of an integrated system, there are still a lot of improvements that need to be done. For example, in the scope of the study, the validation of the thermal assessment result is also not evident. The greatest challenge will be the lack of empirical data, since few studies have been conducted along this line of research investigating the dynamic and behavior-related aspects of pedestrian thermal comfort in Hong Kong. Future work will be dedicated to issues like this. Nevertheless, the objective of this research is to open up new discussions on effective outdoor thermal comfort assessment and the present approach serves as a proof-of-concept of bottom-up outdoor thermal assessment as compared to conventional methods.

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