Energy for Sustainable Development 39 (2017) 82–90

Contents lists available at ScienceDirect

Energy for Sustainable Development

Solar energy model and thermal performance of an electrochromic dome-covered house

Yaolin Lin [a,b,*], Wei Yang [c]

[a] School of Civil Engineering and Architecture, Wuhan University of Technology, Wuhan, Hubei 430070, PR China
[b] Centre for Building Studies, Department of Building, Civil and Environmental Engineering, Faculty of Engineering and Computer Science, Concordia University, 1455 Maisonneuve W., Montreal, Quebec H3G1M8, Canada
[c] College of Engineering and Science, Victoria University, Melbourne 8001, Australia

ARTICLE INFO

Article history:
Received 4 July 2016
Revised 22 October 2016
Accepted 1 May 2017
Available online xxxx

Keywords:
Solar energy model
Thermal performance
Dome-covered house
Sustainable development
Electrochromic glazing

ABSTRACT

A dome-covered house can be considered as a sustainable building design example. It mimicks the optimal forms in the nature, and can help achieve reduction on the house heating energy need in cold winter. When the dome is made of electrochromic glazing, it can prevent large amount of solar energy from passing into the interior of the dome to prevent over-heating in summer. In this paper, a three-dimensional solar energy, thermal and air flow model is presented. The impact of different glazing types on the thermal environment inside the dome in summer and house heating load in winter is investigated. The use of electrochromic/low transmissivity glazing can result in the reduction of the absorption of solar radiation by the ground for up to 88.9%, as compared to the normal glazing and help to reduce the highest air temperature inside the dome from 41.8 °C to as low as 25.6 °C at 1:00 PM on July 21st in Montreal at 45°N latitude, southern part of Canada, and from 34.6 °C to 20.6 °C in Yellowknife at 62.5°N latitude, northern part of Canada, under different control strategies, thus can create a comfortable thermal environment inside the dome.

Introduction

While designers are striving to use material and energy more efficiently, it is expected that much of the conventional, modern architectures are not sustainable over the long term due to their lack of consideration on the interaction between buildings and environment. On the other hand, nature itself has undergone billions of years' evolution and can provide lessons to learn, especially on how to build habitats to integrate harmonily with the environments by the creatures (Tsui, 1999). Design by learning from the optimal forms existing in nature is a possible way towards sustainable buildings since they are selected by nature through billions of years' evolution. Dome mimicks form-optimizing process in the nature and may be represented as pneumatic structure in the architectural world (Stach, 2004; Arslan and Sorguc, 2004). The dome configuration utilizes nature's principles to form a highly efficient system. A dome in northern Canada is a shelter to withstand extreme weather condition, and store large amounts of solar radiation to achieve reduction on the heating energy need of the covered house in the winter.

One zone model (Croome and Moseley, 1984; Luttmann-Valencia, 1990; Singh et al., 2006) and four-zone model (Sharma et al., 1999) were developed to predict the air temperature inside such structure, assuming well-mixed air in each zone. The temperature distribution of the cover was not computed and fixed value of the convection coefficient was imposed, and transmitted solar radiation was simplified by those models (Croome and Moseley, 1984; Luttmann-Valencia, 1990; Singh et al., 2006; Sharma et al., 1999).

Some building energy simulation programs, such as eQuest (2016), can calculate the thermal load of the building, but cannot evaluate the airflow and temperature distribution. EnergyPlus (2016) uses certain room air models to account for non-uniform air temperature by dividing a room vertically into several well separated regions and AirflowNetwork model to calculate the air flow through a set of nodes through linkage. TRNSYS (2016) can be coupled with COMIS for multi-zone air flow calculation where each room is represented as a node. Those programs (eQuest, 2016; EnergyPlus, 2016; TRNSYS, 2016), cannot provide detailed air flow and temperature distribution inside an air space. ESP-r (2016) offers the feasibility of detailed air flow simulation and heat transfer prediction inside a room via CFD. However, it will be extremely time-consuming to applied CFD to a large air space for dynamic simulation.

Lin (2007) developed a transient three-dimensional thermal and air flow model of a house built around a large-scale transparent dome. This

---

* Corresponding author at: School of Civil Engineering and Architecture, Wuhan University of Technology, Wuhan, Hubei 430070, PR China
E-mail address: yaolinlin@gmail.com (Y. Lin).

http://dx.doi.org/10.1016/j.esd.2017.05.001

Nomenclature

A, B, C	solar coefficients;
A_{ij}	cell surface area, m^2;
A_l	wall surface area, m^2;
C_1	coefficient;
C_N	clearness number;
c_p	specific heat of the dome glazing, J/kg °C;
d	thickness of glazing, m;
$f_{h,i}$	hourly usage probability, dimensionless;
$F_{ij,g,out}$	view factor of cell (i,j) to the ground outside, dimensionless;
$F_{ij,l}$	view factor of cell (i,j) to the outside wall surface, dimensionless;
$F_{ij,sky}$	view factor of cell (i,j) to the sky, dimensionless;
$F_{kl,ij}$	view factor of cell (k,l) to cell (i,j), dimensionless;
F_{l-g}	view factor of the outside wall surface to the ground inside, dimensionless;
$I_{beam,ij}$	beam solar radiation over cell (i,j), W/m^2;
$I_{dg,ij}$	incident solar radiation reflected from the outside ground surface to cell (i,j), W/m^2;
$I_{diff,ij}$	diffuse solar radiation over cell (i,j), W/m^2;
$I_{ds,ij}$	diffuse incident solar radiation on cell (i,j) from the sky, W/m^2;
I_{DN}	direct normal incident solar radiation on the earth surface, W/m^2;
I_{max}	maximum allowable beam radiation, W/m^2;
$I_{total,ij}$	total solar radiation on cell (i,j), W/m^2;
k	conductivity of glazing, W/m °C;
$l_{i+1,j}$	length of the border between cell (i + 1, j) and cell (i, j), m;
$P_{i,j}$	power input to the ith electric appliance in phase j, kW;
$q_{conv,ij}$	convection over cell (i,j), W/m^2;
$q_{LWR,ij}$	long-wave radiation heat fluxes with the environment (ground and sky), W/m^2;$q_{sol,ij}$ absorbed incident solar radiation, W/m^2;
$q_{surf,ij}$	long-wave radiation among cell (i,j) and other surfaces, W/m^2;
Q_{HVAC}	thermal load of HVAC system, W; $Q_{internal,conv}$ convective internal heat gain, W;
m_{ij}	mass of one cell (i,j), kg;
$m\cdot_{ij}$	mass flow rate, kg/s;
R	radius of the dome, m;
t	time, s;
T	temperature, °C;
T_a	room air temperature, °C;
T_j	temperature of the jth wall/window/roof/floor surface, °C.

Greek symbols

α_{ij}	absorptance of cell (i,j), deg.;
α_w	absorptance of outside wall surface, dimensionless;
β	solar altitude, deg.;
ρ	air density, kg/m^3;
γ_g	ground reflectance, dimensionless;
θ_{ij}	incident angle over cell (i,j), deg.;
τ_j	time required for phase j, min;
τ_{ij}	transmittance of cell (i,j), dimensionless;
φ	solar azimuth, deg.

model first discretizes the dome cover into a large number of cells to enable detailed calculation of the first and second transmission of solar radiation and variation of the temperature over the dome cover. Next, the air space inside the dome is divided into a large number of zones by using the zonal model approach to calculate the distribution of air flow and air temperature. At the same time, the convection coefficients are treated as variated with a number of factors such as wind speed and wind direction.

This model was used to evaluate the impact of the dome glazing on the house heating energy needs but the impact on the thermal environment in summer was not evaluated. In summer, the dome will become a green house and thus the inside air temperature might increase to a level that will not be thermally comfortable. At the same time, the house occupants' behaviors might have an important impact on the thermal load and energy need of the house (Lin et al., 2015). So, how to estimate the thermal load of the house more accurately and create a comfortable thermal environment inside such structure in summer without air-conditioner?

Electrochromic glazing (ECG) may be used to prevent large amount of solar energy from passing into the interior of the dome roof in summer (Porta-Gándara and Gómez-Muñoz, 2005). ECG has certain advantages over conventional glazing, e.g., fully transparent views can be provided (Lee and DiBartolomeo, 2002); when comparing with conventional fixed shading devices, ECG was found to provide the best performance in reducing solar heat gains (Aldawoud, 2013); ECG can effectively reduce discomfort window glare due to highly bright diffuse skylight when solar radiation intensities are high, while providing much of the available daylight and therefore it is not necessarily to increase the need for artificial lighting and there is no sense of obstruction to the outside (Piccolo and Simone, 2009); the average annual daylight glare index (DGI) can be reduced significantly by electrochromic windows with overhangs and significant annual energy use savings was achieved (Lee and Tavil, 2007).

EC windows could reduce total energy use of ≥45%, peak load carbon emission up to 35% in new construction and 50% in renovation projects for different climate condition in USA (Sbar et al., 2012). For a conference room in Washington DC, EC windows with advanced automated control, thermally improved frames, and dimmable lighting system can save 91% in lighting energy, compared to the existing lighting system (Lee et al., 2012). The use of electrochromic wall can result in total heating and cooling energy savings of 17.6% compared to traditional wall, and of 29.5% compared to Trombe wall in Mediterranean climates (Pittaluga, 2013).

This paper aims at investigating the impact of different types of dome glazing on the thermal environment inside such structure in summer as well as on the reduction of heating load of the house in winter. Three different types of glazing, i.e., normal glazing, ECG under different continuous and discrete control strategies, and glazing with low transmissivity, are analyzed. The transient three-dimensional thermal and air flow model is coupled with control strategies of ECG and occupant behaviors model to be able to predict more accurately on the thermal load of the house and the thermal comfort condition inside the dome. The impact of glazing and control strategies on the reduction of heating load in winter as well as variation of inside air temperature in summer and impact on solar radiation absorbed by the ground inside the dome are presented.

Description and modeling of the problem

Heat fluxes

A schematic diagram on the heat fluxes of the system is presented in Fig. 1. The involved heat fluxes in this system can be summarized as: 1) solar heat gain to the dome cover, ground and house envelop; 2) long-wave radiation among sky, dome surface, ground and house envelop; 3) convection over dome surface, house envelop and ground; 4) infiltration/ex-filtration through the dome and house; 5) conduction through the dome, ground, floor and envelop of the house.