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Three-dimensional thermal and airflow (3D-TAF) model of a dome-covered house in Canada

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Abstract

A dome-covered house is an example of designing sustainable buildings by learning from the optimized biological forms from the nature. The paper presents a 3-D thermal and air flow (3D-TAF) model that estimates the energy needs of a dome-covered house. The model is verified with CFD simulations under the COMSOL Multiphysics environment, experimental measurements and simulation results from similar structures published by other researchers. The use of the dome is expected to reduce the annual heating load of the house by 62.6%, compared with that of an isolated house located in Montreal at 45°N latitude.

Keywords: Dome; Computer simulation; Thermal model; Zonal model; Heating load; Solar energy

1. Introduction

Dome structure is based on the natural form-optimizing process in biological structures and is translated into the architectural world in the form of pneumatic structure [1,2]. The advantages of a transparent dome built above a group of houses in Canada are the following [3]: it can provide a shelter to withstand high winds and extreme temperatures, and it can help for storing solar radiation in the external walls of the house and in the ground. Thus it reduces the heating load of the house in the winter. If the dome is transparent or translucent, it can provide pleasant view without sense of enclosure.

More attention has been given to structural configurations than to the thermal performance of dome-like transparent buildings. Some of the largest geodesic-dome structures, listed in descending order of diameters, are presented in Table 1 [4].

A monolithic dome of about 340 m^2 of living space, having walls and ceiling with the thermal resistances of 10.5 m^2 K/W, and low emissive windows has reduced the energy cost by over $2000 per year compared to a conventional masonry house of the same size [5]. Croome [3] presented his concept of a covered township in the northern part of Canada, using a double layer membrane. By computer simulation he predicted the reduction of about 16% of the annual heating energy needs for houses built under that cover, compared with houses without cover.

Transparent and translucent domes have been used as skylights for daylighting and energy saving purposes. Some models [6–9] have been developed to predict the optical and thermal properties of the dome skylight. Those models replaced single-glazed hemispherical dome skylights by optically and thermally equivalent single-glazed planar skylights. Smith [10] developed a mathematical model that predicts the thermal exchange of a pyranometer, simulated as a small glass dome exposed to natural convection. Electrochromic glazing may be used to prevent the overheating inside such structure in the summer [11].

Only a few thermal models have been presented so far for this type of structure. Croome and Moseley [12]

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Table 1
Largest geodesic-dome structures

No.	Name	Location	Diameter (m)
1	Fantasy entertainment complex	Kyosho Isle, Japan	216
2	Multi-purpose arena	Nagoya, Japan	187
3	Tacoma dome	Tacoma, WA, USA	161
4	Superior dome	Northern Michigan Univ Marquette, MI, USA	160
5	Walkup skydome	Northern Arizona Univ. Flagstaff, AZ, USA	153

developed a quasi-steady state model with one node for the cover and one node for the air inside the dome that predicts the indoor air temperature. They observed that the solution tends to overestimate the air temperature throughout the day because of the model used for coupling the indoor air and ground temperatures inside the dome. Croome and Moseley [13] presented measurements of the air temperature inside an airhouse located in London (UK). Luttmann-Valencia [14] developed a single node model that predicts the air temperature inside Biosphere II, located in Arizona (US). Sharma et al. [15] presented a four-zone model that predicts the air temperature inside a greenhouse, by assuming that there is not air movement between zones. In those models, the air infiltration is either given as the air flow rate [14] or the air change per hour [15]. Singh et al. [16] presented a single node model that predicts the air temperature inside a greenhouse located in Ludhiana (India), by assuming that there is not air movement inside the greenhouse.

Previous models [12–16] did not calculate the temperature distribution over the cover, and a constant value was used for the convection heat transfer coefficient, regardless of the temperature difference, tilted angle, flow direction and variation of air velocity at different locations. Moreover, the temperature variation and air movement inside the dome were neglected, and the distribution of solar radiation inside the dome after the first transmission was simplified.

In this paper, a transient three-dimensional thermal and airflow (3D-TAF) model is proposed for the evaluating of the impact of a large-scale transparent dome on the heating energy needs of a house built inside the dome. The proposed model is verified with results from a CFD model developed under the COMSOL Multiphysics environment, and with measured data and simulation results from similar structures, published by other researchers.

2. Mathematical model

The mathematical model is composed of two components, that is, the thermal model and the air flow model, which are solved iteratively at every time step until the convergence is reached. The thermal model calculates the temperature of some nodes of interest of the simulation domain. The heat balance equations are written for: (a) the dome glazing; (b) the exterior envelope and the floor of the house; (c) the air inside the house; and (d) the earth surface inside the dome. The airflow model calculates the air velocities inside the dome, which are required by the thermal model to estimate the convective heat flow rate at the interface solid–air (e.g., between the dome cover and the dome air). It calculates also the vertical and horizontal temperature gradient of the air inside the dome.

2.1. *Heat balance of the dome glazing*

The dome surface is divided into 42 rows and 13 columns for a total of 546 cells. The coordinates of each cell (i,j) are calculated using a spherical coordinate system. The heat balance equation at the center of each cell (i,j) is written as

$$\begin{aligned} &k \cdot d \cdot l_{i+1,j}(T_{i+1,j} - T_{i,j}) + k \cdot d \cdot l_{i-1,j} \cdot (T_{i-1,j} - T_{i,j}) \\ &\quad + k \cdot d \cdot l_{i,j-1} \cdot (T_{i,j-1} - T_{i,j}) + k \cdot d \cdot l_{i,j+1} \cdot (T_{i,j+1} - T_{i,j}) \\ &\quad + (q_{sol,ij} + q_{conv,ij} + q_{LWR,ij} + q_{surf,ij}) \cdot A_{ij} = m_{ij} \cdot c_p \cdot \frac{dT}{dt}, \end{aligned} \tag{1}$$

where $q_{sol,ij}$ is the absorbed incident solar radiation, in W/m^2; $q_{conv,ij}$ the convective heat flux over the inside and outside cell surfaces; $q_{LWR,ij}$ the long-wave radiation between the cell and the outdoor environment (ground and sky); $q_{surf,ij}$ the net long-wave surface-to-surface radiation between the cell and other surfaces inside the dome; m_{ij} the mass of cell (i,j), in kg; c_p the specific heat of the dome glazing, in J/kg °C; T the temperature, in °C; t the time, in s; k the conductivity of glazing, in W/m K; A_{ij} the surface area, in m^2; d the thickness of glazing, in m, $l_{i+1,j}$ the length of the common border between cell $(i+1,j)$ and cell (i,j), in m; i the row position and j the column position.

2.2. *Heat transfer through walls/roof/floor/ground/window*

Each exterior wall of the house, which is built inside the dome, is assumed to have three layers. The conduction heat transfer through wall/roof/floor/ground is considered to be one-dimensional, and nine nodes are used to discretize each wall/roof. The floor is composed of 100 mm concrete slab and 50 mm insulation. The soil temperature at the depth of 3.0 m is assigned as the boundary condition for the ground inside the dome, while the temperature of the soil surface inside the dome is calculated from the heat balance equation. The temperature of the soil under the floor is assumed to be equal to the temperature of the ground inside the dome at the same depth. The heat transfer through windows is considered as quasi-steady state. Three double-glazing windows are considered, mounted on the south wall, east wall and west wall, respectively.