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Measurement and evaluation of the summer microclimate in the semi-enclosed space under a membrane structure

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This study aims to clarify the summer microclimate in membrane structure buildings with semi-outdoor spaces and develop a computational simulation tool for designing a comfortable urban environment using membrane structures. Field measurements were conducted in a membrane structure building with a semi-outdoor space during a summer period. The present paper describes analysis results of measurement data for vertical distributions of air temperature and velocity under the membrane structure on clear sunny days. The following subjects were also discussed: (1) the effect of solar transmission on the warming of air temperature by the floor under the membrane structure; (2) the temperature reduction effect of ventilation by wind; (3) evaluation of thermal comfort in the living space under the membrane structure in terms of a thermal comfort index (new standard effective temperature: SET*).

In order to demonstrate the capability to improve the thermal environment in the test membrane structure building, an evaporative cooling pavement was assumed to be applied to the ground under the membrane structure. The microclimatic modifying effect of this passive cooling strategy was evaluated using a numerical simulation method of coupling computational fluid dynamics (CFD) with a 3D-CAD-based thermal simulation tool developed by the authors' research group. Simulation results show that the proposed simulation method is capable of quantifying spatial distributions of surface temperature, air temperature, air velocity and moisture in the living space under the membrane structure. The thermal comfort index (SET*) can also be estimated using these simulated results.

1. Introduction

Public facilities such as roofs of outdoor passages and bus stations constructed of membrane structures are increasing in recent years. One of the reasons for this increase is considered to be that a large built space can be created by a membrane material which is very light and highly transparent. In addition, highly solar-reflective and thin membrane materials absorb little solar heat and keep their surface temperatures low when irradiated by solar radiation. Furthermore a semi-enclosed (semi-outdoor) space can also be created under these membrane structures. As a result, both daylighting and natural ventilation can be provided. Therefore, as a passive system providing solar shading and ventilation as well as daylighting, a membrane structure building would play an attractive role in improving outdoor thermal environments and mitigating the heat island effect in the developed urban locations.

Many previous studies have been carried out on membrane structure buildings with enclosed indoor spaces such as atrium and dome spaces where air-conditioning is required. As one of these previous studies, Kim et al. [1,2] studied indoor environments and air exchange rate in arcade-type markets with different building sizes and roof materials. Both heating and cooling are required in these targeted interior spaces. As one of previous studies on the non-air-conditioned space, Tsujihara et al. [3–5] have carried out a field measurement to investigate the thermal environment in an enclosed arcade where the roof is made of glass. In one recent study, Elseragy and Elnokaly [6] examined the microclimatic modifying effects of various forms of the roof beneath which there is an un-enclosed space. At present there is still a lack of studies on membrane structure buildings with semi-outdoor spaces that are not air-conditioned zones.

Thus, the current authors have conducted field measurements to investigate the microclimate in a membrane structure building with a semi-outdoor space during a summer period. Our previous paper [7] has reported the measurement and simulation results

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Nomenclature

a,b	constants in Brunt's equation
a_s	solar absorptance
A_B	total body's surface area of the human (m^2)
A_r	effective radiation area of the human (m^2)
C_1,C_2,C_3	constants in the turbulent equation
c_m	specific heat of humid air (J/(kg K))
c_p	specific heat (J/(kg K))
C_μ	constant in the turbulent model
D_m	water vapor diffusivity (m^2/s)
D_{mt}	turbulent water vapor diffusivity (m^2/s)
e	water vapor pressure near the ground (Pa)
F_i	weighting factor for face i
g_i	gravity acceleration in i direction (m/s^2)
h_c	convection coefficient (W/(m^2 K))
h_r	radiation heat-transfer coefficient through clothing (W/(m^2 K))
I_{Ai}	sky solar radiation to face i (W/m^2)
I_{DR}	direct solar radiation (W/m^2)
I_{Li}	total longwave radiation to face i (W/m^2)
I_{Ri}	reflected solar radiation to face i (W/m^2)
I_{RR}	reflected solar radiation (W/m^2)
I_{Si}	total solar radiation to face i (W/m^2)
I_{SR}	sky solar radiation (W/m^2)
k	turbulent kinetic energy (m^2/s^2)
L	latent heat (J/kg)
MRT	mean radiant temperature (K)
MRT*	mean radiant temperature for an environment with solar radiation (K)
N	number of adjacent surfaces
p	pressure (N/m^2)
Pr_t	turbulent Prandtl number
q	specific humidity (kg/kg(DA))
Sc_t	turbulent Schmidt number
t	time (s)
T	temperature (K)
T_0	reference temperature (K)
T_a	air temperature (K)
T_s	surface temperature of a mesh (K)
T_{si}	surface temperature of adjacent surface i (K)
U	velocity (m/s)
U_0	velocity at a reference height (m/s)
u_i	velocity components in i direction (m/s)
x	coordinates in the normal direction to a mesh surface (m)
x_i	three components of coordinates (m)
X_a	absolute humidity mixing ratio at temperature of T_a (kg/kg (DA))
X_s	absolute humidity of saturated air at temperature of T_s (kg/kg (DA))
Z	height from the ground (m)
Z_0	reference height (m)

Greek symbols

β	evaporation efficiency
ε	dissipation rate of turbulent kinetic energy (m^2/s^3)
ε_i	emissivity of adjacent surface i
ε_s	emissivity of a mesh surface
λ	thermal conductivity (W/(m K))
λ_t	turbulent thermal conductivity (W/(m K))
η	volumetric expansion coefficient of air (K^{-1})
θ	incident angle of direct solar radiation (rad)
μ	kinematic viscosity coefficient (kg/(m s))
μ_t	eddy viscosity coefficient (kg/(m s))
ρ	density (kg/m^3)
σ	Stefan–Boltzmann constant (W/(m^2 K^4))
$\sigma_k,\sigma_\varepsilon$	constants in the turbulent equation
σ_t	constant in the turbulent equation
ϕ	azimuth angle (rad)
Φ_i	view factor from a point to adjacent surface i
Φ_{sky}	view factor from a point to the sky

focused on the thermal radiation environment in the membrane structure building. The present paper focuses on the microclimate and deals with the following subjects: (1) the effect of solar transmission on the warming of air temperature by the floor under the membrane structure; (2) the temperature reduction effect of ventilation by wind; (3) evaluation of thermal comfort in the living space under the membrane structure. In addition, a case study is also carried out using a coupled simulation method in order to quantify the microclimatic modifying effect of a passive evaporative cooling pavement on the semi-outdoor environment in the test membrane structure building.

2. Field measurement

2.1. Description of the test membrane structure

The test membrane structure building is located at Yokohama in Japan (35°20′ north latitude, 139°38′ east longitude) and used as a leisure/rest space in an amusement park. A bird's-eye view and south view of the membrane structure are shown at the left and right of Fig. 1, respectively. The east and west sides of the space under the membrane structure (called under-membrane space hereinafter) are opened to outdoors. The sea is on the east side of the test membrane structure. The under-membrane space at a height of 1.2 m above the ground is called the living space under the membrane in this paper. The south and north sides are two-story buildings (stores, restaurants, etc.) made of reinforced concrete. The under-membrane space is 20 m wide, 15 m high and 42 m deep. The membrane is supported by metal hollow pillars and stretched by wires, looking like a wavy surface in a suspension structure. The solar reflectance, absorptance and transmittance of the membrane material are 0.74, 0.17 and 0.09, respectively. As illustrated in Fig. 2, most of the ground under the membrane is covered with wooden tiles. The surface material of the ground near the walls on the south and north side of the under-membrane space is concrete tile.

2.2. Measurement methods

The main measurement location is at the center of the under-membrane space at a height of 1.2 m above the ground as shown in Figs. 2 and 3. The following measurements were conducted at the main measurement location: incoming solar radiation (including solar transmission and reflected solar radiation) from six directions ((1) east, (2) south, (3) west, (4) north, (5) roof and (6) floor), air temperature, relative humidity, air velocity and spherical thermograph (surface temperature distribution in the under-membrane space).

Vertical distributions of air temperature, relative humidity and air velocity were measured at locations h_1–h_4 indicated in Figs. 2 and 3.