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Thermal performance of stadium's Field of Play in hot climates

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ABSTRACT

The stadium Field of Play (FoP) is a large area of grass that affects the stadiums overall thermal performance. This paper experimentally and numerically investigates the thermal performance of stadiums FoP in hot and arid climates. For a period of one year, the temperature readings of the FoP natural grass surface, subsoil at a depth of 200 mm and the surrounding running track were recorded for Khalifa stadium in Doha, Qatar. The temperature measurements were used to assess the accuracy of numerical predictions of the stadium FoP temperature distribution using two different numerical methods. First, a Direct Numerical Simulation (DNS) model was developed to simulate the unsteady heat transfer between the atmosphere and natural turf, and between the soil and turf. The DNS model accounts for radiative, convective, conductive and evaporating heat on the surface for different climates. Second, a prognostic three-dimensional ENVI-met climate model was utilized to simulate the stadium FoP microclimate system. Although the measured and simulated data showed good agreement, differences were noticed at the peak temperatures. In winter and spring seasons, the peak temperature predicted by the DNS model appeared one hour later than the measured peak temperature, while the ENVI-met predicted peak temperature was detected two hours later. The difference is attributed to the treatment of soil thermal capacity and its water content. Both of the numerical models considered the soil temperature as constant near the averaged measured soil data. For the grass surface and subsoil, the DNS model could better predict the temperature change during the day of the four seasons. The research results can be utilized to validate the thermal models proposed to simulate stadiums thermal performance.

1. Introduction

Stadiums and arenas have large volumes. Hence, variations of air temperatures and velocities within the volume can be very notable. It is vital to ensure favorable thermal comfort conditions that are acceptable to spectators and players. Stadiums with canopies are considered as semi outdoor environments, such the approach for comfort models should address indoor and outdoor characteristics with the solar irradiance [1–6]. Stadiums have a relatively large area of natural turf that offers a suitable environment to footballers to play all year round. The stadium FoP is of a rectangular shape, with the touchline to be longer than the goal line. The FoP should have a minimum length of 90 m, and a maximum of 120m; and a minimum width of 45 m, and a maximum of 90 m giving a minimum FoP area of 4050 m^2 and a maximum FoP area of 10800 m^2. For international matches, the FoP specifications are of 100 m to 110 m in length and 64 m to 75 m in width [7].

Stadiums FoP climate conditions are critical, as mandatory cooling breaks were established by FIFA under certain environmental conditions of heat and humidity in order to prevent the development of heat related illness of players and referees. In any location or environmental condition known to be hot and/or humid, the Wet Bulb Globe Temperature (WBGT) is measured 90 min and repeated 60 min before the start of the match. Should either of the WBGT readings are at or above 32 °C, mandatory cooling breaks are undertaken or the match may be either postponed or cancelled, depending on the level of the WBGT reading [58]. Qatar has an arid

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Nomenclature

D	Thermal diffusivity (m^2/s)
$R_{s,\max}$	Maximum solar radiation (W/m^2)
T	Temperature (°C)
T_a	Dry bulb temperature (°C)
T_f	Grass layer temperature in (°C)
T_{fk}	Grass layer temperature in (K)
T_G	Globe temperature (°C)
T_w	Wet bulb temperature (°C)
$WBGT$	Wet bulb globe temperature (°C)
c_f	Foliage bulk transfer coefficient (m)
$h_{evap,f}$	Grass layer evaporative heat fluxes (W/m^2)
$h_{evap,g}$	Evaporative heat flux at the ground surface (W/m^2)
$h_{conv,f}$	Grass layer convective heat fluxes (W/m^2)
$h_{conv,g}$	Convective heat flux at the ground surface (W/m^2)
h_{ro}	Surface runoff heat transfer rate (W/m^2)
h_{ii}	Incoming long wave radiation
$h_{net,g}$	Net heat flux to the ground (W/m^2)
$h_{rad,g}$	The net radiative flux between grass layer and ground (W/m^2)
$h_{rad,net,g}$	Net radiative heat flux at the ground surface (W/m^2)
q_a	Ambient specific humidity (kg_w/kg_a)
q_{sat}	Saturated specific humidity (kg_w/kg_a)
r_a	Aerodynamic resistance coefficient (s/m)
r_s	Stomatal resistance coefficient (s/m)
t	Time (s)
α_f	Grass layer albedo (dimensionless)
α_g	Ground albedo (dimensionless)
ε_f	Grass layer emissivity (dimensionless)
ε_g	Ground emissivity (dimensionless)
ν	Vegetation density (0–1, dimensionless)

desert-like climate, with hot summers, high ambient mean relative humidity of 43% and 72% in June and December respectively, negative water deficit due to scarce precipitation and warm winters [5,6].

Large natural grass areas can influence the urban microclimate affecting the outdoor air quality and the energy use of buildings. The total heat load of an air conditioned stadium is resulting mainly from infiltrated wind through the stadium oculus, sun radiation during day time, sensible and latent heat from spectators, sensible and latent heat from FoP and other electric equipment and lighting fixtures. Typically, an air conditioned stadium, designed for hot and arid areas like the Middle East and North Africa (MENA) region, have a typical heat load of about 70,000 kW. When calculating the stadium heat load, an accurate estimation of the FoP heat load and grass surface temperature is a vital input to the stadium thermal numerical simulations.

Previous relevant studies investigating the effect of grass and vegetation on urban cooling can be categorized into two areas; studies concerning dynamic thermal modeling of heat transfer through the soil and the planted cover and vegetation effect on urban cooling. Numerical modeling can be used to estimate the soil temperature for any given values of soil surface heat flow and to predict the heat flow through the soil [8]. The author argued that the dependence of the soil temperatures on the environmental conditions is strong, since the soil temperature is immediately affected by radiation fluxes. Carson [9] argued that within different depths, the soil temperature values present significant fluctuations due to the soil properties and the seasonal climatic conditions. Exchanges of heat in the soil are strongly dependent on the amount of water on the surface [10,11]. Presence of groundwater can also affect land surface temperatures [12]. The study revealed that transpiration is noticed from all the soil layers that the root is distributed, while evaporation on the top layer is responsible for the reduction of the soil's moisture. The authors attempted to identify Groundwater Dependent Vegetation (GDV) by modeling land surface temperatures, concluding that the approach is able to map the presence of groundwater. Thus, the hydrological cycle has an impact on modeling soil properties. Herb et al. [45] simulated an unsteady, and one-dimensional model of seven different land surfaces after rain episodes namely pavements, bare soil, short and tall grass, a forest, and two agricultural crops (corn and soybeans). The authors considered that the surfaces presented low and high amount of water, so to determine effects from urbanization. Best [13] modeled vegetation close to the ground such as crops and grass, excluding tall trees using different meteorology variables namely air temperature, dew-point temperature, wind speed, low, medium and high cloud amounts, and an indication of periods of precipitation. Temperature prediction was achieved by constructing thermal contrasts patterns between the surfaces such as bare soil and sand. The author concluded that, modeling of vegetation temperature requires modeling of the energy balance of the foliage and the substrate separately. Vogel et al. [14] applied the Penman–Monteith big-leaf approach for multi-layer canopies, concluding to the efficiency of the model especially when the vegetation is of high density. Givoni and Katz [15] approached soil temperature exponentially as temperature waves, in terms of depth and time. Kusuda [16] obtained hourly soil measurements 9 m (30 ft) blow the ground, to solve the heat equation for a semi-infinite solid where its surface temperature was presenting sinusoidal behavior, without taking into consideration variations in daily temperature. Penrod et al. [17] used monthly average temperatures in a sod-covered clayey soil for a five yearly norm. The authors investigated how soil temperatures at different depths are affected by the solar radiation received on the surface. Mihalakakou et al. [18] obtained seventy-four years of ground temperature measurements at various depths and compared them with predicted values, extracted from truncated sine wave and exponential models. The values resulted in good agreement. Jacovides et al. [19] performed Fourier analysis for temperatures at the surface and at various depths and for both bare and short-grass-covered areas. Mihalakakou [20] modeled the transient heat conduction and the energy balance at the ground for predicting soil surface temperature. An analytical and a neural network models were compared with real data from Greece and Ireland, proving their accuracy in estimating soil surface temperature distribution. Qin et al. [21] presented a surface energy numerical balance model applying the Crank–Nicolson implicit method. The authors coupled soil temperature changes with the amount of water shifting within the soil, for a desert in South Israel. Results highlighted solution difficulties. Other thermal model studies include complicated mathematical models considering effect of leaf shades and heat lost by transpiration [22–26].

Environmental modeling has been a major component of the scientific approach in understanding and solving problems in complex environmental settings. Different climate conditions lead to multiple thermal sensations due to the variety of microclimatic data [5,6]. The authors modelled an outdoor air-conditioned area, named as the FANZONE for identifying occupants outdoor thermal comfort during sport events. Modeling of tree shading and evapotranspiration rates, that affect energy fluxes, can offer valuable analysis of the microclimate conditions of urban green spaces to optimized outdoor comfort [27]. Urban feature modelling helps authorities to take decisions about land-use options and development patterns for creating sustainable urban environments [28,29]. ENVI-met is a commercial software developed to simulate Urban Heat Island (UHI). Adaptive use of modeling software, such as ENVI-met advances the environmental design, planning and intervention processes. The software can estimate the impact of the urban