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Performance analysis of a planted roof as a passive cooling technique in hot-humid tropics

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ABSTRACT

Planted roofs are passive cooling techniques that reduce the thermal load of buildings. In this paper, the authors have developed a model for evaluating the cooling potential of green roofs. Transfer equations are solved using a finite difference scheme and Thomas algorithm. The study was conducted taking into account the Togolese climate conditions. The effect of Leaf Area Index (LAI) and Biot (Bi) number on diurnal variation of the Solar Heat gain Factor (SHF) is presented and analysed. A correlation for the estimation of the Solar Heat gain Factor as a function of LAI and Bi has been established. The results presented in terms of evapotranspiration (ET) and Solar Heat gains Factor (SHF) show notably that the foliage density and hence the vegetable canopy type selection influence the thermal efficiency of the bioclimatic insulation screen greatly. It was found that a larger LAI reduces the solar flux penetration, stabilizes the fluctuating values, and reduces the indoor air temperature.

1. Introduction

In hot tropical climates, thermal loads are very high and induce an unbearable environment inside buildings. The gains through the fabrics of buildings are due to the heating effect of absorbed solar radiation transferred to the interior. In practice, the estimation of the cooling energy of a building takes into account the various thermal loads through the side walls, glazing, the air infiltrations and leakage (renewable air), the internal gains of the building (lighting, occupancy, electric equipment, etc.) and particularly, the elements of the roof.

A priori, it is more rational to reduce a cause of heating than to offset the heat load by increasing the cooling efficiency. On the other hand, a good thermal protection can greatly reduce the high thermal loads thereby improving thermal comfort in a hot-humid tropical building. The gains through the fabrics of the building can be minimized by: the use of shading to reduce the amount of radiation falling on the building, the reduction of the absorbed radiation through the use of highly reflective finishes, the increase of the insulation value of the roof and walls.

For years, many researchers have shown the role of building materials, the lens hoods or fixed overhanging roofs and building orientation on the improvement of thermal comfort in buildings. Some studies show that about 30–50% of the heat gains inside buildings are brought about by elements of the roof [1]. Various experimental studies proved that the heat gain through the roof can be reduced by white paint, layers of wetted gunny bags, a water pond with moveable insulation and water spreading equipment [1–3].

In hot-humid climates, some methods or techniques are better adapted to improve thermal comfort in buildings. Particularly, the use of attic void with thin sheeting roofs [4,5], and thermal insulation screens (ground layer, extruded or moulded polystyrene plates, plaster false ceiling, and vegetation covers) underneath and above the concrete flagstone roof reduces the heat load in a building [5,6]. Technically, these insulation screens are integrated beneath reinforced concrete flagstone as an additional insulation sublayer. In fact, green roofs present a very effective and positive impact on the urban climate and microclimate as well as on the indoor temperature of buildings beneath them. In closed spaces with planted roofs, the air temperature beneath the plants during sunny time is lower than that of the air above. For their biological functions, such as photosynthesis, respiration, transpiration and evaporation, foliage materials absorb a significant proportion of solar radiation and contribute to reduce heating loads of buildings in the highest solar irradiation regions [7]. A green roof offers a building and its surrounding environment many benefits. These include storm water management [8,9], improved water run-off quality [10], improved urban air quality [11], extension of roof life

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[12] and a reduction of the urban heat island effect [13]. Other benefits include enhanced architectural interest and the protection of biodiversity [14].

For many years, planted roofs have been a familiar construction in some countries. During the last few decades, due to climatic changes and especially the heat island effect in urban areas and the continuous destruction of green areas, planted roofs have been frequently referred to because of their ecological character and their contribution to energy conservation in the building sector. The application of bioclimatic concepts in the urban sector is limited by the fact that the very dense built environment does not permit the utilization of vertical surfaces for passive solar strategies. Even the simplest technique, such as natural ventilation, is not always applicable since air pollution and noise in the urban built environment lead to a need for air-tight buildings. At the same time, in a hot-humid tropical climate, roofs of buildings receive high thermal stress during sunny day and they require strong measures in order to prevent excessive heat gains.

Planted roofs are often said to be in a position to offer adequate solutions to this problem. However, despite research that has been carried out so far, planted roofs are still a solution, which is proposed mainly for qualitative rather than quantitative reasons, since as a passive cooling technique they still cannot be a part of a building simulation study.

The present study aims mainly to analyse the effect of vegetation screen on the heat gains in buildings. The determination of temperature variations has allowed to deduce daily variation of the evapotranspiration rate, which naturally established the surrounding microclimate. A useful parameter such as the dynamic Solar Heat gains Factor (SHF) which in the best case must be less than 4% [15], is the main control variable evaluated.

2. Model description and assumptions

The green roof system studied is composed of five interacting subsystems: the atmosphere above canopy, the vegetation canopy, the soil, the flagstone and the indoor air (see Fig. 1). The parameters defining the outdoor conditions are the solar radiation and the radiant fluxes coming from the sky, the ambient air humidity and temperature, the wind direction and speed. The roof is considered large enough and assumed horizontally homogeneous. Heat and mass fluxes are assumed to be mainly vertical so that one-dimensional models are used to describe the thermal behaviour in the roof components. A reference is chosen at ground level at soil-canopy interface and the abscissas are counted positively in the sense of plant growth (Fig. 1).

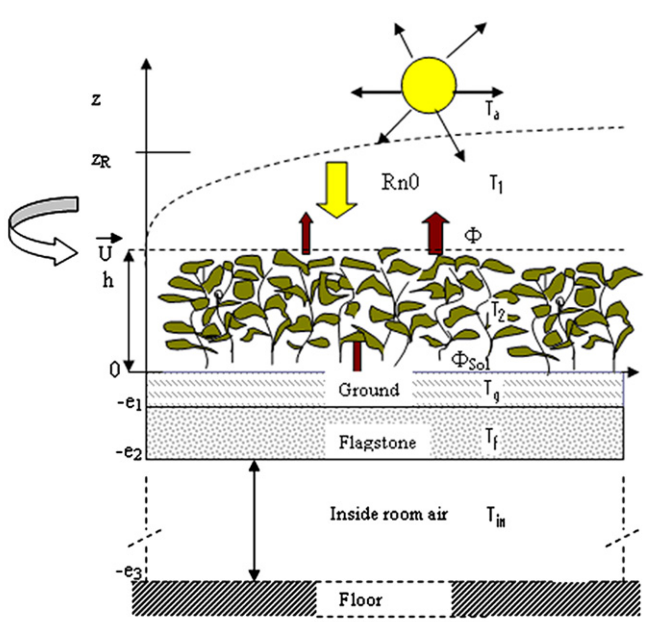

Fig. 1. Schematic of a green roof.

Transport process is considered unsteady and the turbulent airflow is incompressible. The following additional assumptions are made in the analysis.

- The photochemical energy is neglected as well as viscous heat dissipation
- Thermal diffusion and inter-diffusion effects are neglected in comparison with turbulent diffusion
- Pressure gradient effects are neglected
- Thermodynamic and thermo-physical properties of Water vapour are functions of composition
- The underground of the vegetation canopy is assumed homogeneous and saturated with water
- The indoor air layer is motionless
- The thermo-physical properties of the roof support are constant
- The radiant fluxes from the leaves are neglected.

3. Governing equations

3.1. Indoor air layer model

Taking account of one of the assumptions about the indoor air layer, the convective heat transfer is neglected. Consequently, the heat transfer equation is written as:

$$(\rho c_p)_{\text{in}} \frac{\partial T_{\text{in}}}{\partial t} = \frac{\partial}{\partial z}\left(\lambda_{\text{in}} \frac{\partial T_{\text{in}}}{\partial z}\right) \tag{1}$$

3.2. Roof support model

The roof support is a homogeneous flagstone (cement concrete).

$$(\rho c_p)_f \frac{\partial T_f}{\partial t} = \lambda_f \frac{\partial^2 T_f}{\partial z^2} \tag{2}$$

3.3. Soil model

$$(\rho c_p)_g \frac{\partial T_g}{\partial t} = \frac{\partial}{\partial z}\left(\lambda_g \frac{\partial T_g}{\partial z}\right) \tag{3}$$

3.4. Vegetable canopy model

The canopy is composed of the leaves and the air within the leaf cover. It is a complex system of sources and sinks of heat and mass such that an exact description of its physical behaviour is almost impossible. While attempting to figure out a simpler model of a canopy, one is faced with two types of problems. The first is the inherent spatial complexity and dishomogeneity of the foliage. This implies that for an accurate description, the number of simultaneous equations to be solved could be five times higher than the number of leaves in the canopy. The second is the turbulent nature of the air stream within a canopy. Its consequence is that the direction and magnitude of the fluxes of energy and mass vary at any moment and cannot be exactly predicted. In spite of this, in much of the literature concerned with the coupling of plants with their environment, heat and mass transfer to and from a canopy are