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***RESEARCH ARTICLE***

# VEGETATION INSULATION SCREEN AS A PASSIVE COOLING SYSTEM IN HOT HUMID CLIMATE: HEAT AND MASS EXCHANGES

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## Abstract

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Planted roofs are passive cooling techniques that reduce the thermal load of buildings. In this paper, a Dynamic mathematical model based ontime average Navier-Stokes equationsfor a plantedroof in hothumidclimates has beendeveloped for evaluating the cooling potential.Transfer equations are solved using a finite difference scheme and Thomas algorithm. The model was applied for the simulation of a planted roof in Togolese climate conditions. Results showed that, evapotranspiration and Solar Heat gain Factor are functions of the Leaf Area Index LAI which is the most important parameter when considering the foliage material. For LAI equal to 6, latent heat peak value reaches 900 $W.m^{-2}$ while that of sensible heat is around 350$W.m^{-2}$. Solar heat gain factor can bereducedto 15% fortheplantedroofagainst 45% forbareroof. It is clearly proved that the foliage density and hence the vegetation canopy type selection greatly influence the thermal efficiency of the bioclimatic insulation screen. A larger Leaf Area Index reduces the solar flux penetration and increases evapotranspiration which is an important parameter when considering surrounding microclimate formation.

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## Introduction:-

Metallic and concrete roofs are very common in buildings in most of the developing countries particularly in tropical regions. The temperatures inside such buildings are far beyond the comfortable conditions in these regions. The direct cooling devices are electrically operated and are not feasible due to unreliable supply of electricity. In such a situation, passive cooling techniques are very appropriate to provide comfort. Passive cooling of buildings can be defined in several ways [1, 2, 3]. One way is to consider any treatment of the building which reduces its cooling load, such as solar control and minimizing internal heat gains. Studies in the literature show that about 30 to 50% of the heat gains inside a building are brought about by elements of roof [1]. In hot-humid climates, somemethods or techniques are better adapted to improve thermal comfort in buildings. Particularly, the use of thermal insulation screens (ground layer, extruded or moulded polystyrene plates, plaster false ceiling, vegetation canopy) underneath and above the concrete flagstone roof reduces the heat load in a building [4, 5]. The insulation screens are integrated beneath reinforced concrete flagstone as an additional insulation sublayer. The aim of the vegetation surface on roof top design concept is to reduce the heat gain and minimize the cooling load for mechanical air-conditioning. The field study shows that the passive cooling of planted roofs is recognized as one of the effective energy saving means

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in buildings in warm-humid climates and reduces the indoor air temperature within comfort range. It influences the use of the electrical cooler and air conditioning of the indoor space. Therefore, it can reduce the energy demand of the building which saves a lot of money for the daily electricity bill of urban residents [6]. The green roof plants generate oxygen and provide worth for air pollution control and soil erosion. Green roofs reduce the carbon level that controls global warming. Planted roofs present a very effective and positive impact on urban climate and microclimate as well as on the indoor air temperature of buildings beneaththem. In closed spaces with planted roofs, the air temperature beneath the plants during sunny times 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 heat gains inside a building in the highest solar irradiation regions [7]. With rapid urbanization, there has been high growth in population and building construction in cities. A high concentration of buildings actually raises many environmental issues, such as the Urban Heat Island effect. This effect started mainly because of the loss of green areas in the urban environment. Plants when strategically placed around roofs, can be considered a complement of urban greens. These provide visual enhancement, noise control, storm water management, improved water run-off quality, improved urban air quality, extension of roof life, reduction of the urban heat island effect, architectural design and biodiversity. This natural solution also contributes to the thermal benefits in buildings and their surrounding environments.Greenery placed around buildings serves to reduce the surface temperature through direct shading of hard surfaces as well as cool the ambient air through absorbing solar heat for transpiration and photosynthesis [8]. The shaded surfaces also emit less long-wave radiation due to lower surface temperature. All these contribute to lowering energy consumption for cooling and mitigating Urban Heat Island effect in the urban environment. Modelling green roof should be useful for engineer in optimization of such a passive system in practical buildings. The present study aims mainly to model green roof and analyze the effect of vegetation cover on internal heat gains of a building.

Important parameters which affect the surrounding environments such as evapotranspiration have been analysed as well as sensible and latent heats fluxes. To analyse heat and mass transfer through theplanted roof system, useful parameters such as Nusselt and Sherwood numbers have been used asmain control variables.

## Model Description and Assumptions:-

The green roof system studied is composed of four interacting subsystems: atmospheric environment above the canopy, the vegetation canopy, the soil and the flagstone. Figure 1 shows the physical model while the figure 2 gives a view of green roof. The parameters defining the outdoor conditions are the solar radiation, the radiant flux coming from the sky, the ambient air humidity and temperature and 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 model is used to describe the thermal behaviour in the roof components. A reference is chosen at the ground level at soil-canopy interface and the vertical axis is counted positively in the sense of plant growth (figure 1). 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 inhomogeneity 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 described as vertical fluxes along a concentration gradient across some typical resistances. For a given vegetation canopy, the leaf and the stalk constitute obstacles to airflow and are characterised by the Leaf Area Density LAD(z). This scalar is assumed to be a vertical distribution function. In leaf gas exchange studies, the variable employed to characterise the atmospheric water stress was the leaf-to-air saturation deficit *Y(z).* This scalar is defined as the difference between dry and wet air bulk temperatures:$Y(z)=T(z)-Tr(z)$

The transpiration rate depends on the bulk stomatal coefficient $\alpha(z)$ which plays the same role as bulk stomatal resistance r(z) of the plants reported by most authors. The coefficient $\alpha$ is equal to 0 for the dry foliage plants and 1 for the wet foliage. When the vegetation canopy is very dry, evaporation comes under the physiological control of the plant, as it has to pass through the stoma. The bulk stomatal resistance of the canopy is expressed using the Noilhand and Planton correlation [9], the factors considered here are a solar radiation factor $f_1$, a water stress factor $f_2$, a factor related to atmosphere pressure deficit $f_3$ and an air temperature dependence factor $f_4$. These different factors $f_i$ are detailed in the reference [10].

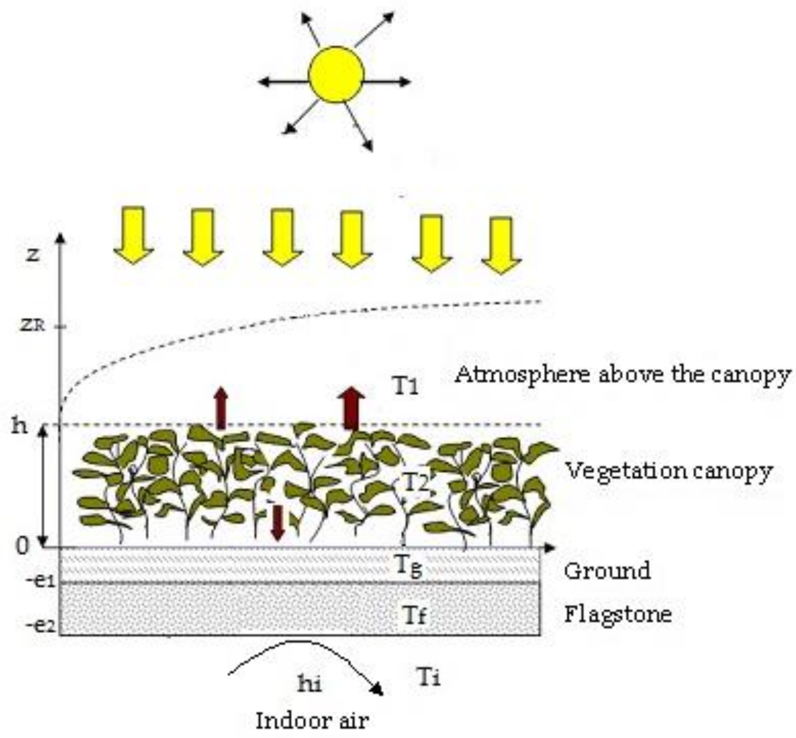


**Fig.1:-**Sketch of a green roof.

$$r(z) = \frac{r_{\min}}{LAI} f_1(\phi) f_2(\omega) f_3(P_{VST} - P_V) f_4(T_S - T_2) \quad (1)$$

Transport process is considered unsteady and the turbulent airflow is incompressible. In the atmosphere above the canopy and within the vegetation, time-average Navier-Stockes equations for one-dimension are considered. The following additional assumptions are made in the analysis.

**Fig.2:-** View of some green roofs.

1. The photochemical energy is neglected as well as viscous heat dissipation,
2. Thermal diffusion and inter-diffusion effects are neglected in comparison with turbulent diffusion,
3. Pressure gradient effects are neglected,
4. Water vapour thermodynamics and thermo physical properties are functions of composition.
5. The underground of the canopy is assumed homogeneous and saturated with water.
6. The thermo physical properties of the roof support are constant
7. The radiant fluxes from the leaves are neglected.

8. The thermal inertia of the plants (leaves and stalk) is neglected so the heat and vapour source-sink terms are expressed as follows:

$$S_T(z) = \rho Cp h_T(z) LAD(z)(T_S - T_2) = \left( \frac{d\phi(z)}{dz} - \frac{d\phi_L}{dz} \right) \quad (2)$$

$$S_{C(z)} = h_M(z) LAD(z)(C_S - C_2) = \frac{1}{L_V}\left( \frac{d\phi_L}{dz} \right) \quad (3)$$

The source of latent heat flux (intensity) is given by:

$$\frac{d\phi_L}{dz} = \frac{\varpi}{\varpi+\gamma}\alpha(z)\left[\frac{d\phi(z)}{dz} + \rho Cp h_T LAD(z) Y(z)\right] \quad (4)$$

$$\alpha(z) = 1/\left(1 + \frac{\gamma}{\varpi+\gamma}\left[h_T(z) r(z) + (Le)^{-2/3} - 1\right]\right) \quad (5)$$

The parameters $h_T$ and $h_M$ are respectively heat and mass vapour convective transfer coefficients calculated from empirical correlations [11].

$$h_T(z) = h_0 u(z)^{0.8} \quad (6)$$

$$h_M(z) = (Le)^{2/3} h_T(z) \text{ for } u(z) \leq 4m/s \quad (7)$$

**Governing Equations**

Conservation of energy in the roof and soil.The soil and the roof support are considered as homogeneous mediums and are described by a heat transfer equation expressed as:

$$(\rho c_p)_k \frac{\partial T_k}{\partial t} = \frac{\partial}{\partial z}\left( \lambda_k \frac{\partial T_k}{\partial z} \right) \quad (8)$$

In the equation 8, the index $k = g$ for the soil layer and $k = f$ for the concrete roof.

*Conservation of Momentum*

The momentum equation inside and above the vegetation canopy is written as follows.

$$\frac{\partial u}{\partial t} = \frac{\partial}{\partial z}\left[(\nu+\nu_t)\frac{\partial u}{\partial z}\right] - \frac{1}{2} C_d LAD(z) u^2(z) \quad (9)$$

The additional term of the equation 9 describes the effect of canopy elements drag on airflow. In this equation $C_d$ is an effective drag coefficient of the vegetation canopy. Above the vegetation canopy, $C_d$ and *LAD(z)* are equal to zero.

*Conservation of vapour and energy within and above the vegetation canopy*

$$\rho Cp \frac{\partial T_j}{\partial t} = \rho Cp \frac{\partial}{\partial z}\left[K_T(z)\frac{\partial T_j}{\partial z}\right] + S_T(z) \quad (10)$$

$$\frac{\partial C_j}{\partial t} = \frac{\partial}{\partial z}\left[K_C(z)\frac{\partial C_j}{\partial z}\right] + S_C(z) \quad (11)$$

Above the vegetation canopy : $j = 1$ and $LAD(z)=0$

Within the vegetation canopy: $j = 2$ and *LAD(z)* is assumed symmetric towards the h/2.

The Leaf Area Density variation is sinusoidal in the z-direction and is expressed by:

$$LAD(z) = \pi \, LAI \, Sin(\pi z / h) / 2h \text{ with } 0 \leq z \leq h \quad (12)$$

The air saturation deficit equation is expressed as follows

$$\frac{\partial}{\partial z}\left[K_T(z)\frac{\partial Y(z)}{\partial z}\right]-LAD(z)\alpha(z)Y(z)+\left[\frac{1-\alpha(z)}{\rho Cp}\right]\frac{d\phi(z)}{dz}=0 \tag{13}$$

The net radiation is determined in any given layer within the vegetation canopy using the following relation:

$$\phi(z)=\phi_0\exp\left[-0.65.\,LAI(z)+0.05\,LAI(z)^2\right] \tag{14}$$

$\phi_0$ is the global solar radiation measured at the reference height.

*Initial and Boundary Conditions*

Thetemperature, water vapour density and velocity are initialized as follows:

$$U(z,0)=U_a\ T_2(z,0)=T_a$$
$$T_1(z,0)=T_a\ C_2(z,0)=C_a$$
$$C_1(z,0)=C_a\ T_g(z,0)=T_0$$
$$T_f(z,0)=T_a\ T_i(z,0)=T_0 \tag{15}$$

The boundary conditions at the reference height at$z=z_R$, are expressed as follows:

$$U(z_R,t)=U_a\ T_1(z_R,t)=T_a \tag{16}$$
$$C_1(z_R,t)=C_a\ Y(z_R,t)=Ya \tag{17}$$

The interfacial conditions are:

Atmosphere above canopy-Canopy coupling model

$$\phi(h)=-L_V K_M(z)\frac{\partial C_1}{\partial z}\bigg|_{z=h}-\rho C_p K_T(z)\frac{\partial T_1}{\partial z}\bigg|_{z=h}+\rho C_p K_T(z)\frac{\partial T_2}{\partial z}\bigg|_{z=h} \tag{18}$$

$$K_M(z)\frac{\partial C_1}{\partial z}\bigg|_{z=h}=K_M(z)\frac{\partial C_2}{\partial z}\bigg|_{z=h} \tag{19}$$

Canopy-soil coupling model

$$\phi(0)=-L_V K_M(z)\frac{\partial C_2}{\partial z}\bigg|_{z=0}+\lambda_g\frac{\partial T_g}{\partial z}\bigg|_{z=0}+\rho C_p K_T(z)\frac{\partial T_2}{\partial z}\bigg|_{z=0} \tag{20}$$

$$K_T=\left(\nu/\Pr+\lambda_t/\Pr_t\right)\text{and}\ K_M=\left(\nu/Sc+\nu_t/Sc_t\right) \tag{21}$$

Soil-Roof support (Flagstone) coupling model

$$\lambda_g\frac{\partial T_g}{\partial z}\bigg|_{z=-e_1}=\lambda_f\frac{\partial T_f}{\partial z}\bigg|_{z=-e_1} \tag{22}$$

Flagstone-indoor air coupling model

$$\lambda_f\frac{\partial T_f}{\partial z}\bigg|_{z=-e_2}=h_i(T_f-T_i) \tag{23}$$

## Numerical Procedure:-

Transfer equations with appropriate boundary conditions are solved numerically using an implicit finite difference scheme and Thomas algorithm. The diffusion terms are approximated by the central finite difference scheme and the implicit procedure to discretize the temporal derivatives is retained. For a given temperature at substrate-canopy and canopy-atmosphere interfaces and under initial conditions, water vapour, heat and momentum transfer equations are solved in each zone. The following time and spatial steps Δt =10 s and Δx = 0.005 m are respectively retained. Successive iterations were applied and the solution is considered satisfactory when the following convergence criterion is verified for each time:

$$\left|\left(\phi_{i,j}^{k+1} - \phi_{i,j}^{k}\right)/\phi_{i,j}^{k}\right| \leq 10^{-5} \tag{24}$$

$\phi$ can be the temperature T or the water vapour density

## Results and Discussion:-

The daily ambient temperature and solar radiation are assumed to have a sinusoidal variation during a day. For a given ambient temperature and relative humidity, the dew points are deduced from Mollier's psychometric chart. The saturation deficit scalars of the air as well as the water vapour density at the reference height are calculated. Particular attention is paid to characteristic fluxes such as evapotranspiration, sensible and latent heats fluxes. The local heat gain across the planted roof is evaluated in terms of solar heat gain factor. For a given value of wind speed in greenery, effects of solar radiation and canopy structure (Leaf Area Index LAI) on evapotranspiration, sensible and latent heats fluxes are illustrated in figures and analysed. The determination of water vaporization and its transfer to substomal cavities according to climatic characteristics, canopy structure and stomatal regulation is an essential point in the understanding and interpretation of evapotranspiration. Indeed, hourly evapotranspiration is obtained by summing hourly values of local latent-heat flux from different layers within the canopy and added to the hourly value of evaporation at substrate's level. The evolution of evapotranspiration density as a function of the incident solar flux density is illustrated in Figures 3. The evapotranspiration varies linearly as a function of solar radiation density. The characteristic result of evapotranspiration for different values of Leaf Area Index LAI show how evapotranspiration evolves over a sunny day. An increase in LAI value resulting from vegetation canopy density increases the evapotranspiration value. It's clear that evapotranspiration is more important when the foliage is sufficiently dense.

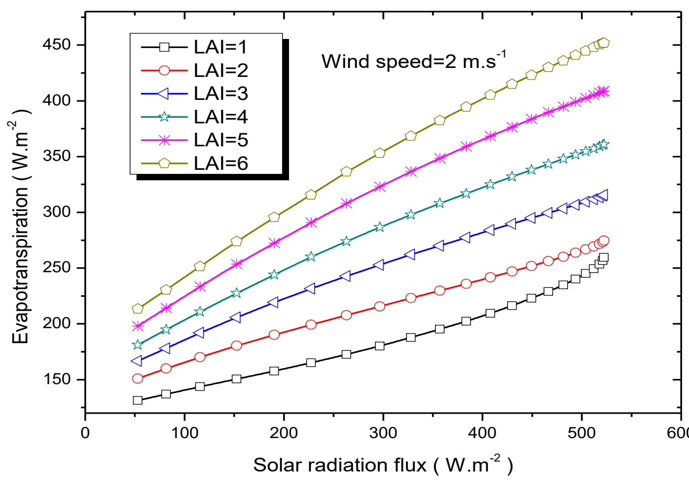


**Fig.3:-** Evapotranspiration as a function of solar radiationdensity.

Net radiation in the canopy is a function of *LAI(z)*; therefore, for a high value of LAI, transpiration heat flux is more important and heat removal involves a decreasing of temperature within the canopy. In fact, according to the intensity of the latent heat flux which depends directly upon biological regulation, each part of the plants becomes a local source of heat for weak evaporation or local sink of heat for strong evapotranspiration. In figures 4 and 5 are illustrated the variation of the sensible and latent heat fluxes at different hours of a day. As expected, according to the leaf density area distribution, maximum transpiration source occurs at the mid-height $h/2$ of the vegetation canopy. A striking decrease in transpiration is observed in the upper and lower parts of the canopy. The distribution of the leaf area density plays a very important role in heat and mass exchange in the canopy. The symmetrical distribution adopted leads to a local latent heat flux density that decreases from mid-canopy height to the soil surface under the canopy as shown in Figure 4. This decrease is more or less modified by the value of stomatal resistance

that can reduce, by stomatal closure, water loss, and energy loss by sensible heat flux and the increase in surface temperatures. A strong stomatal regulation in the upper part of the canopy could lead to a maximum flux density of local latent heat. A specific arrangement of the orientation of the sheets with a minimum captation of radiation in the upper part of the canopy may also lower the maximum flux density of local latent heat. For low foliar coverage, local latent heat flux density is not high enough since the maximum obtained around 2 p.m is about 250 W.m$^{-2}$ while in the case of a dense canopy, this flux density can reach about 900 W.m$^{-2}$.
The local density of sensible heat flux evolves in more complex manner with mostly positive values in the upper parts of the canopy, sometimes turning negative in the lower parts as it's shown in figure 5. Heat flux exchange from the canopy to the atmosphere explained the positive values of sensible heat flux while negative values obtained mostly for large values of LAI are explained by the diffusion of the accumulated heat in canopy towards the colder substrate.

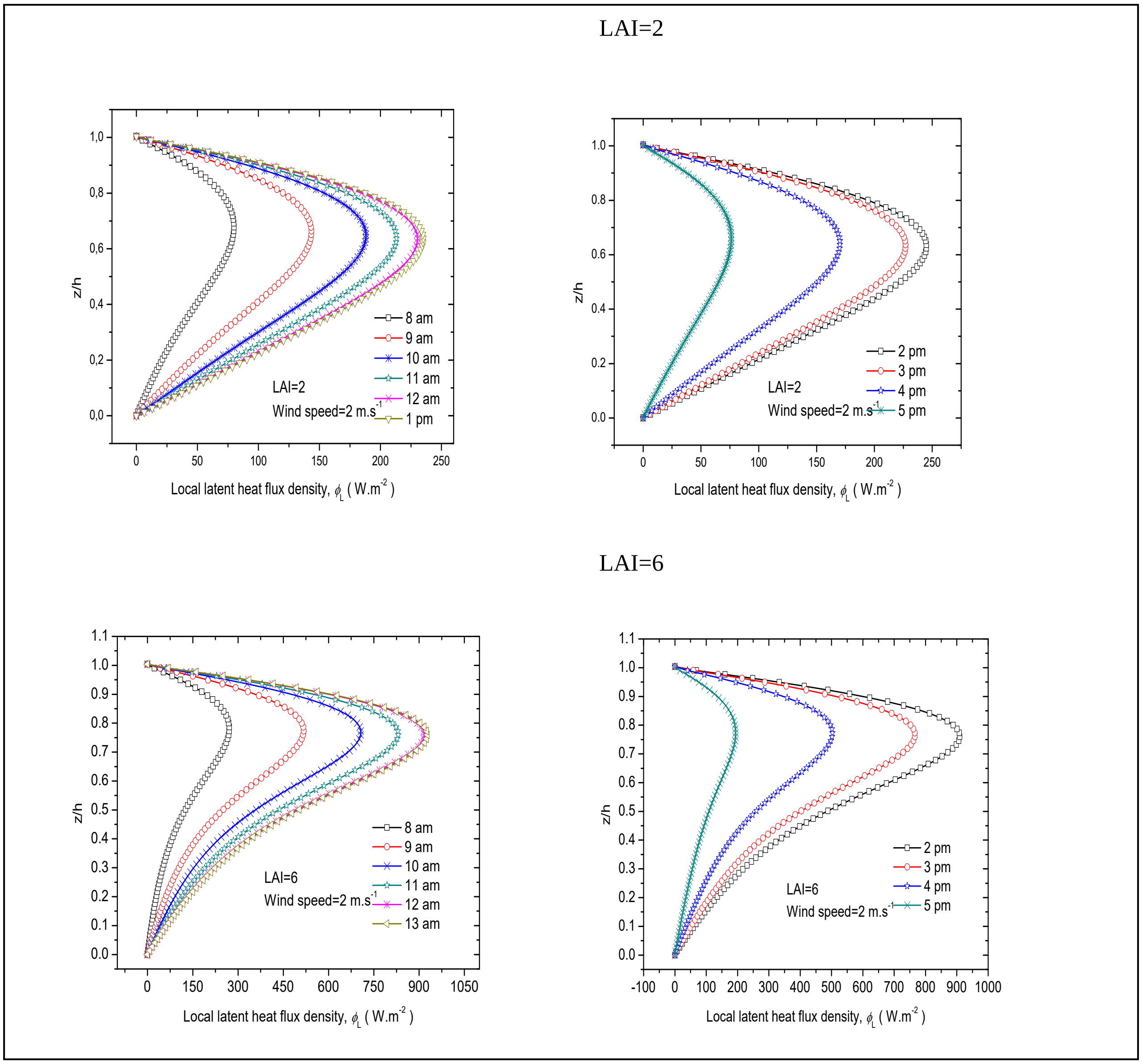


**Fig.4:-** Local latent heat flux density profiles within the canopy

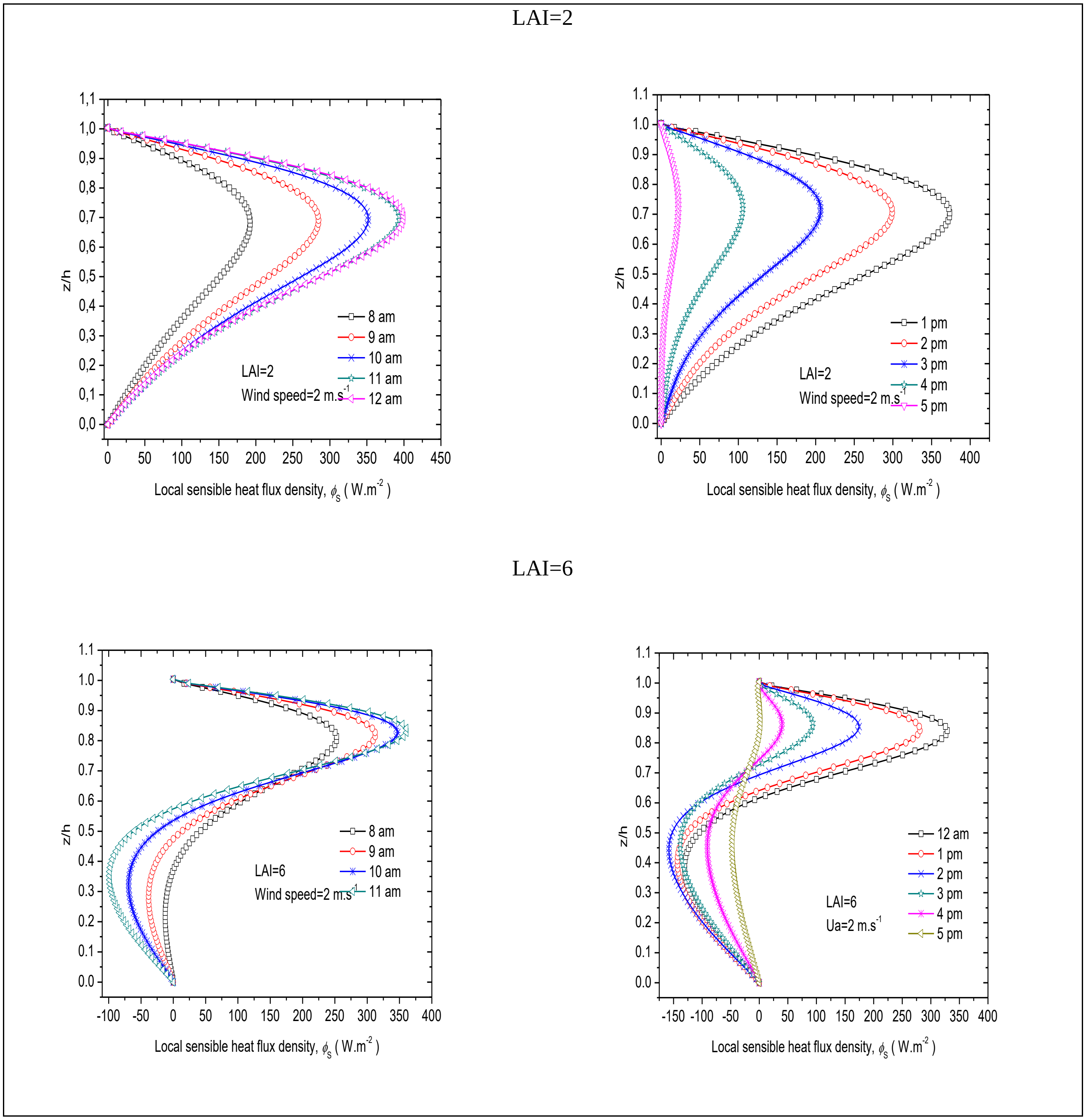


**Fig. 5:-** Local sensible heat flux density profiles within the canopy

Figure 6 illustrates the temperature profiles of the substrate surface for different LAI values. This figure shows that an increase in LAI causes a decrease in temperatures. A fairly dense vegetation cover considerably reduces the growing medium temperature. This is explained by the fact that the net radiation is strongly mitigated by the leaf material and by the activity of the stomata which are more numerous. In general, the growing medium surface temperature is sensitive to climatic factors, the type of vegetation cover is highly dependent on the state of drought of this layer.

Phenomena of heat and mass exchanges modelling are described in terms of Nusselt and Sherwood numbers. Figure 7 presents respectively the variations of the Nusselt and Sherwood numbers as a function of the solar radiation density for differents values of LAI. The both two transfer numbers evolve linearly as a function of solar radiation. For a given LAI, the intensity of heat (Figure 7 (a)) and water vapor (Figure 7 (b)) transfer at the vegetation-atmosphere interface intensify when increasing solar radiation density which in fact controls the stomata regulation. The profiles of transfer numbers increase with the value of LAI. For high values of LAI, transpiration flux increases significantly and exchanges of heat and water vapor between the vegetation and the atmosphere are very important as shown by the variations of the Nusselt and Sherwood numbers.

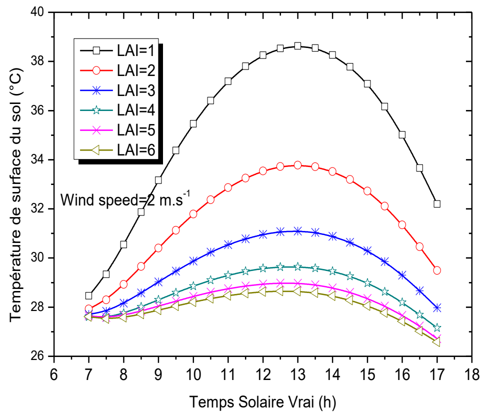


**Fig.6:-**Evolution of surfacetemperature of the substrate.

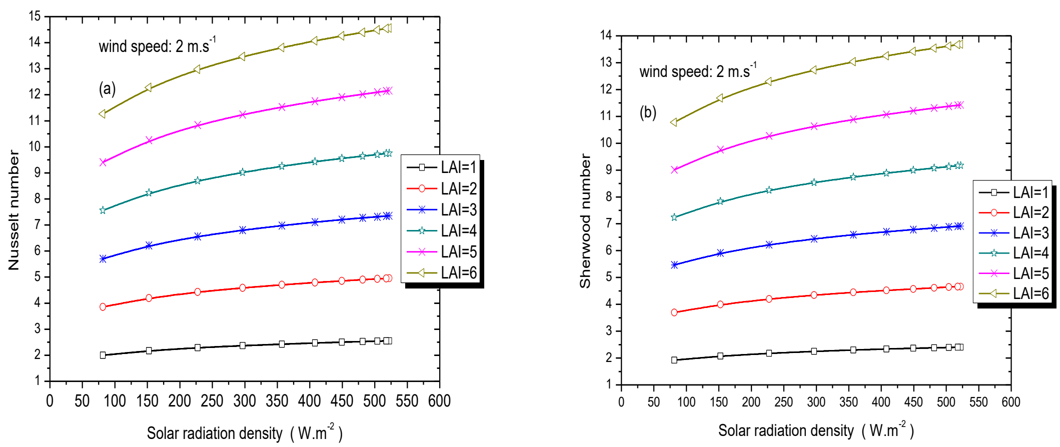


**Fig.7:-** Nusselt (a) and Sherwood (b) numbers as a function of solar radiationdensity.

When considering the degree to which solar gain is transmitted by the fabric of the building, it is helpful to use the concept of solar heat gain factor. This is a useful parameter defined by Koenigsberger [12] as the heat flow rate through the construction due to solar radiation expressed as a fraction of the incident solar radiation. In the present study, the solar heat gains factor of the green roof is defined as the ratio of transmitted solar energy into the interior of the building to incident solar energy. This factor has been calculated for the planted roof and for the roof without vegetation canopy. Figure 8 clearly indicates that, the vegetation canopy significantly reduces the heat gain in the building. Indeed, without greenery on the roof top, the solar heat gain factor can reach a maximum value of 45% against 15% for a roof with vegetation canopy (LAI = 3). In addition, the solar heat gain factor remain less the 5 % on a long period of a suny day until 2 p.m.

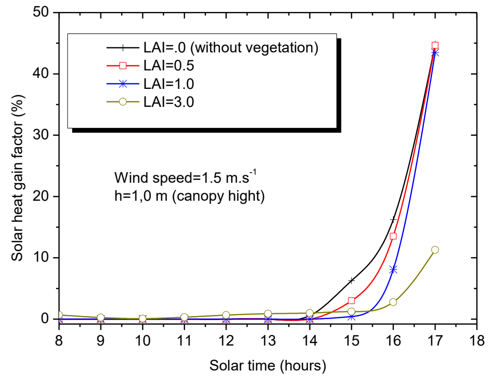


**Fig. 8:-**Hourly evolution of solar heat gain factor.

## Conclusion:-

A dynamic mathematical model based on time average Navier-Stokes equations for a planted roof in hot humid climates has been developed. The effectiveness of vegetation screen as a passive cooling technique is examined theoretically and compared with a classical roof in hot-humid climate conditions.

The results showed that, for LAI equal to 6, latent heat peak value can reach 900 W.m$^{-2}$ while that of sensible heat is around 350 W.m$^{-2}$. It was found that solar heat gain factor can be can reduced to 15% for the planted roof when considering LAI=3 against 45% for for bare roof. It is clearer, that cooling load in buildings can be reduced by the application of such bioclimatic screen design. Evapotranspiration and Solar Heat gain Factor are functions of Leaf Area Index which is the most important parameter when considering the foliage density. It is clearly proved that the foliage density and hence the vegetation canopy type selection greatly influence the thermal efficiency of the bioclimatic insulation screen. A larger Leaf Area Index reduces the solar flux penetration and increases evapotranspiration which is an important parameter when considering surrounding microclimate formation.

Before, adoption of such a technique in hot humid climate, studies must be conducted not only on plants species selection suitable with minimum maintenance but also on the resistance of species selected to drought and their water consumption for possible application to the arid regions.

**Nomenclature**

**Letters**

C (z) water vapour density distribution (kg.m$^{-3}$)
$C_{2S}$ water vapour density distribution on the surface of layers (kg.m$^{-3}$)
Cp specific heat (J.kg$^{-1}$.K$^{-1}$)
$C_d$ canopy effective drag coefficient
Ca water vapour density distribution at the reference height (kg.m$^{-3}$)
H height of canopy (m)
$h_T$ convective heat transfer coefficient (W.m$^{-2}$.K$^{-1}$)
$h_M$ convective water vapour transfer coefficient (W.m$^{-2}$.K$^{-1}$)
$h_C$ convective heat transfer coefficient (W.m$^{-2}$.K$^{-1}$)
Hr relative humidity (%)
$I_0$ solar constant (W.m$^{-2}$)
Le Lewis number (Le=1.2)
$l$ mixinglenght (m)
Lv latent heat of vaporisation (Jkg$^{-1}$)
LAD(z) leaf Area Density (m$^2$.m$^{-3}$)
LAI (z) total Leaf Area Index of the vegetation canopy
Pr Prandtl number
Prt turbulent Prandtl number
Pv water vapour pressure (Pa)
Pvs saturation water vapour pressure (Pa)
r(z) stomatal resistance (s.m$^{-1}$)

$r_{Min}$ minimal stomatal resistance ($s\ m^{-1}$)
t time (s)
T(z) temperature distribution (°C)
Tg soil temperature (°C)
Ts surface cover temperature (°C)
Tr dew point temperature (°C)
Ta water vapour temperature at the reference height (°C)
u(z) wind velocity distribution ($ms^{-1}$)
Ua wind velocity at the reference height ($m.s^{-1}$)
Y(z) air saturation deficit scalar distribution (°C)
z vertical coordinate (m)
$z_0$ roughness length (m)
$z_R$ reference height (m)

**Greek symbols**
$\nu$ molecular cinematic viscosity
$\mu$ turbulent dynamic viscosity
$\gamma$ psychometric constant
$\rho$ air density ($kg.m^{-3}$)
$\phi(z)$ local solar heat flux density ($W.m^{-2}$)
$\phi_S$ sensible heat flux density ($W.m^{-2}$)
$\phi_L$ latent heat flux ($W.m^{-2}$)
$\phi_0$ solar radiation at $z_R$ ($W.m^{-2}$)
$\lambda$ thermal conductivity ($W.m^{-1}.K^{-1}$)

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