II-572 Coupling of Vapor and Heat Transport Underground in Normal Meteorological Conditions: A Numerical Modelling

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1 Introduction

Nowadays, with the development of cities and industrial areas, heat island problem becomes a serious environmental problem. The surfaces covered by pavement can absorb a large amount of heat in day time and release it to the atmosphere in night time. Study of evaporation from soil surface and under surface heating processes needs coupling of the transport of water vapor and heat in an unique model. No researcher has attempted a model, which can predict the transport of water vapor under a paved surface although it is believed that this phenomenon is very important for the transfer of heat.

This paper presents a unidimensional numerical modeling of the coupling of mass and heat flow under surface of bare soil and paved surfaces. The partition of net flux of radiant energy at the surface is also evaluated.

2 Theory and Model Development

The study is based mainly on the theories of Philip and de Vries (1957) and de Vries (1958) about the coupling of heat and mass transfer inside porous media. The matric head is used as an independent variable following Milly (1982). The governing equations are as follows. For the pavement, the thermal characteristics of concrete or asphalt are assumed constant. So inside the pavement slab, $0 \le z \le l$, the heat conservation equation is

$$\rho_1 C_1 \frac{\partial T}{\partial t} = K_1 \frac{\partial^2 T}{\partial z^2} \qquad (1)$$

where z is the downward vertical coordinate of the point, t is time, T is temperature, l is the thickness of the cover slab, ρ_1 is the density, C_1 is the heat capacity and K_1 is the heat conductivity of the pavement material. The equations of mass and heat conservation inside soil underneath, $z > l$, are as follows

$$\left[\left(1-\frac{\rho_v}{\rho_l}\right)\frac{\partial \theta}{\partial \psi} + \frac{\theta_a}{\rho_l}\frac{\partial \rho_v}{\partial \psi}\right]\frac{\partial \psi}{\partial t} + \left[\left(1-\frac{\rho_v}{\rho_l}\right)\frac{\partial \theta}{\partial T} + \frac{\theta_a}{\rho_l}\frac{\partial \rho_v}{\partial T}\right]\frac{\partial T}{\partial t}$$
$$= \nabla.[(K + D_{\psi v}) \nabla \psi + (D_{Tv} + D_{Ta}) \nabla T] + \frac{\partial K}{\partial z} \qquad (2)$$

$$\left[C + L\theta_a \frac{\partial \rho_v}{\partial T} - (\rho_l W + \rho_v L)\frac{\partial \theta}{\partial T}\right]\frac{\partial T}{\partial z} + \left[L\theta_a \frac{\partial \rho_v}{\partial \psi} - (\rho_l W + \rho_v L)\frac{\partial \theta}{\partial \psi}\right]\frac{\partial \psi}{\partial t}$$
$$= \nabla[\lambda \nabla T + \rho_l(LD_{\psi v} + gTD_{Ta}) \nabla \psi] - c_l q_m \nabla T \qquad (3)$$

where ρ_l is the liquid water density, K is the hydraulic conductivity, $D_{\psi v}$ is the matric head diffusivity of vapor in $\psi - T$ system, D_{Tv} is the temperature diffusivity of vapor in $\psi - T$ system, D_{Ta} is a transport coefficient for absorbed liquid flow due to thermal gradient, ψ is matrix head, λ accounts for the combined effect of simple Fourier heat diffusion and latent heat transport by temperature-induced vapor diffusion, L is latent heat of vaporization of water, c_l is specific heat of liquid water, g is gravity acceleration, T_0 is some reference temperature; θ is volumetric liquid water content, θ_a is volumetric air content, ρ_v is density of water vapor.

The upper boundary condition is the mass and heat flux at the surface. The mass flux is evaporation rate e minus rainfall rate r_f

$$q_m = e - r_f \qquad (4)$$

The heat flux at the surface is the solar radiation S, the net long wave radiation R_n, the turbulent diffusion sensible heat H, the sensible heat carried by rainwater and in case of bare soil, the latent Le and sensible heat carried away by water vapor. Then at the surface

$$-K\frac{\partial T}{\partial z} = S(1-\alpha) + R_n + H - Le - c_l(T - T_0)e + c_l(T - T_0)r_f \qquad (5)$$

In case of the paved surfaces, the condition at the contacted surface is the continuation of temperature and heat flux. The lower boundary condition is that at large depth, the temperature and matric head are kept constant. The initial conditions are the matric head and temperature, given as a function of z at the time of the beginning of computation

A numerical modelling of fully implicit scheme finite difference type was developed to solve the mass and heat transfer equation inside soil in case of bare soil (equations (2), (3)) and heat conduction in the covering slab (equation (1)), heat and mass transfer inside underlying soil (equations (2), (3)).

3 Results and Discussions

The data needed for the calibration of the model were based on a experiment conducted at the Environmental and Hydraulic Laboratory, Saitama University (Asaeda et al. 1991). The data were on 26th and 27th of August, 1991.

On figure 2 are the comparison between observed and computed temperature under surface of bare soil and surfaces covered by concrete, asphalt of the thickness 10 cm at 7 o'clock, 12 o'clock, 18 o'clock and 24 o'clock of 25th August, 1991. It is clear that there is a good fit between computed and observed data, suggesting that the model works well in our condition.

Study of the change of vapor head and moisture in the soil indicated that in day time, when soil temperature increased, water in the soil was evaporated and vapor was transported downwards. One part of energy conducted into soil would be used for evaporation of water and the transport of water vapor downwards would carry another part of this energy downwards in the form of sensible heat. So with the evaporation of water and downward transfer of water vapor, the temperature at the surface can be reduced. In night time, when surface temperature reduces, water vapor inside soil would be condensed and the upward transfer of water vapor would carry heat upwards. To study the role of water vapor movement to subsurface temperature distribution and the effect of global warming to heat island problem, the thickness of covering slab and air temperature were increased. The computational results indicate that in these cases, heat island problem becomes more serious.

Understanding the partition of net radiation at the surface to heat fluxes is very important for the prediction of atmospheric dynamical processes near surface, environmental conditions of atmosphere and surface. The net flux radiation, turbulent diffusion sensible heat, latent heat in case of soil surface and conduction heat to deeper layer are depicted on figure 2. It is clear that for paved surface, in day time, the conduction heat to deeper layer is large and this amount of heat will be released to atmosphere in night time.

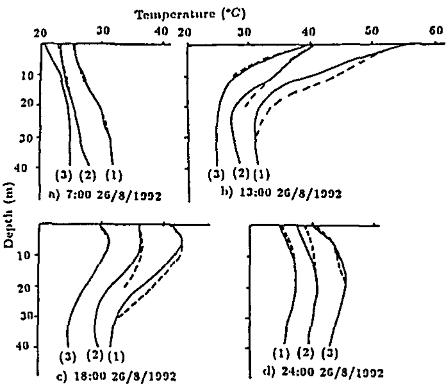

Fig. 1 Computed and Observed Temperature at Different Times
— Computed Temperature -- Observed Temperature
(1) Asphalt (10 cm) (2) Concrete (10 cm) (3) Bare Soil

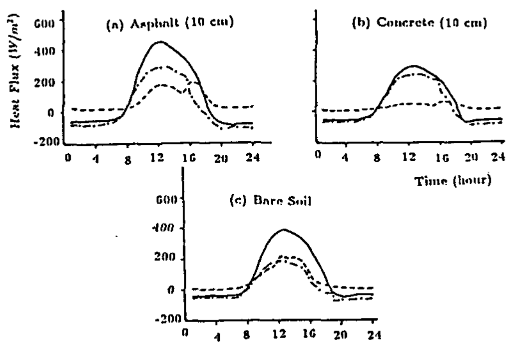

Fig. 2 Net Flux Radiation, Turbulent Diffusion Sensible Plus Latent Heat, Conduction Heat to Deeper Layer from Different Surface
— Net Flux Radiation -- Turbulent Diffusion Sensible Plus Latent Heat
—·— Conduction Heat to Deeper Layer

4 Conclusion

The results show that the transportation of water vapor inside soil has an important effect on the subsurface distribution of temperature, especially for bare soil. Because of evaporation, temperature of bare soil is much lower than that under the covered surfaces throughout of a day and temperature of the surface covered by asphalt is extremely high and higher than atmospheric temperature even in night time.

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