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Research Paper

A time and wavelength dependent heat and mass transfer model

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ABSTRACT

This work presents a representation of the heat and mass processes dependent on wavelength spectrum which acts in a radiative cavity filled with a fluid mixture and interfaced with a porous medium. The formulation mainly aims to account for the wavelength dependent response of the transparent solid material and all involving constituents in order to improve the simulation of their radiation interaction. The model is based on a set of governing equations of mass, momentums and energy balance approximated by a finite-difference scheme and some empirical relations. The model is validated against data measured in a field experimentation of a greenhouse. The reasonable agreement between numerical and experimental results, in term of temperature and water mass content of fluid and porous medium, demonstrate the effectiveness of the proposed numerical model.

1. Introduction

Heat and mass transfer in a solid cavity filled with a fluid mixture and interfaced with a porous medium, concerns a wide variety of practical problems, agriculture greenhouses, engineering materials, industrial and food processing, energy storage [1–3]. Heat transfer in solid and porous medium [4] when radiation transfer is predominant over conduction and convection ones has been considered in scientific works, above all for high temperatures [5–7] or transparent-greenhouse systems [8–11].

Numerical modeling is a widely employed tool in heat flux and mass flux prediction of the response of a physical system although it remains complementary to experimental data. Numerical simulation of energy and mass exchange between physical components should account all the heat transfer modes: conductive, convective and radiative. Generally, the radiative mode transfer is approached by not effectively considering direction and diffuse wavelength variability of radiation participating elements. This approach can be around acceptable only when the elements are opaque not, instead, when the elements are semi-transparent.

The proposed model is physically based and split into its participating sub-systems, in a modular-type mode. This seems advantageous when wavelength-dependent and multiple scattering radiative variables deeply regulate energy gain. Other models such as empirical ones use parameters with no physical inference and, being strongly dependent on input data, they can drop for applicability away from their strictly validation field.

This work proposes a representation of the physical processes dependent on wavelength spectrum which acts in a radiative cavity system. The present approach takes into account the monochromatic variability of absorptivity, transmissivity and reflectivity of all the involving constituents, semi-transparent and grey bodies [12–14]. The model is validated upon an experimental data set measured in field, from Sivolella [15], for a case study of a greenhouse-soil system.

The model is based on a set of governing equations of mass, momentums and energy balance approximated by the Finite Difference Method (FDM) [16–17]. As starting point of the discretization process the FDM uses the strong or differential form of the governing equations, instead other available methods, Finite Volume Method (FVM) [18] and Finite Element Method (FEM) [19], use the weak or integral form of the governing equations, by reducing requirements on the regularity or smoothness of the solution. They can be advantageous, against FDM, to treat boundary conditions and discontinuity. However, the FDM has been chosen in this work mainly for its straightforwardness to implement in software code.

2. Materials and methods

The numerical model is applied to study the heat and mass behavior of a greenhouse as shown in Fig. 1a, under climate and

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Nomenclature

$\underline{\mathbf{a}}_\lambda, a_\lambda$	monochromatic direct, diffuse absorptivity, dimensionless
A	area of the surface, m^2
c_p	specific heat at constant pressure, J kg^{-1} K^{-1}
d	characteristic dimension, geometrical distance, m
D_{Tl}	thermal diffusivity for liquid phase, m^2 s^{-1} K^{-1}
D_{Tv}	thermal diffusivity for vapor phase, m^2 s^{-1} K^{-1}
D_{wv}	moisture diffusivity for liquid phase, m^2 s^{-1}
D_{wl}	moisture diffusivity for vapor phase, m^2 s^{-1}
D_w	diffusivity of water vapor, m^2 s^{-1}
$\underline{\mathbf{e}}_\lambda, e_\lambda$	direct, diffuse emissivity, dimensionless
$\underline{\mathbf{E}}_\lambda, E_\lambda$	monochromatic direct and emissive power, Wm^{-2}
F	view factor, dimensionless
$\underline{\mathbf{f}}$	vector of body force for unit volume, kg s^{-1} m^{-2}
g	acceleration of gravity, 9.81 ms^{-2}
$\underline{\mathbf{G}}_\lambda, G_\lambda$	direct, diffuse received incident radiative heat flux, Wm^{-2}
h	convective heat transfer coefficient, Wm^{-2} K^{-1}
H	hydraulic conductivity of water in soil, m s^{-1}
k	conductivity heat transfer coefficient, Wm^{-1} K^{-1}
i	internal energy per unit mass for the fluid, J kg^{-1}
l_i	leaf area index, dimensionless
L	latent heat of vaporization of water, J kg^{-1}
$\underline{\dot{\mathbf{m}}}$	mass rate flow for unit area, kg s^{-1} m^{-2}
$\dot{m}$	specific rate of mass generation, kg s^{-1} m^{-2}
$\underline{\dot{\mathbf{q}}}$	vector of the rate water mass generation per unit volume, kgm^{-3}
$\underline{\dot{\mathbf{m}}}_l$	water liquid flux, kg s^{-1} m^{-2}
$\underline{\dot{\mathbf{m}}}_v$	water vapor flux, kg s^{-1} m^{-2}
$\dot{m}_{ov}$	mass rate flow of vapor phase, in the moist-air mixture, at open windows, kg s^{-1} m^{-2}
$\dot{m}_{fv}$	mass rate flow of vapor phase, in the moist-air mixture, at porous medium fluid interface, kg s^{-1} m^{-2}
$\dot{m}_{cv}$	vapor phase mass flow rate, in the moist-air mixture, from vegetation, kg s^{-1} m^{-2}
Nu	Nusselt number, dimensionless
$\underline{\mathbf{n}}$	unit outward normal vector, m
Pr	Prandtl number, dimensionless
p	partial pressure, Pa
p_t	atmospheric pressure, Pa
p_v	water vapor pressure, Pa
p_{vsat}	saturation water vapor pressure, Pa
$\dot{q}$	specific rate of heat generation, Wm^{-2}
$\underline{\dot{\mathbf{q}}}$	heat flux vector per unit area, Wm^{-2}
$\underline{\mathbf{r}}_\lambda, r_\lambda$	monochromatic direct, diffuse reflectivity, dimensionless
$\underline{\mathbf{R}}_\lambda, R_\lambda$	direct, diffuse radiosity, Wm^{-2}
R_g	gas constant, J kg^{-1} K^{-1}
Re	Reynolds number, dimensionless
$\underline{\mathbf{S}}, S$	solar direct, diffuse irradiance, Wm^{-2}
Sc	Schmidt number, dimensionless
$\underline{\mathbf{t}}_\lambda, t_\lambda$	monochromatic direct, diffuse transmissivity, dimensionless
t	time, s
T	temperature, K
$\underline{\mathbf{v}}$	fluid velocity vector, ms^{-1}
$\underline{\bar{\mathbf{v}}}$	bulk velocity vector, ms^{-1}
$\underline{\mathbf{x}}$	point position vector in a Cartesian system, m
x, y, z	point position coordinates in a Cartesian system, m
X	air humidity ratio, kg^1 kg^{-1}

Subscripts

a	air phase
b	blackbody
c	vegetation
cri	critical
d	dew point
e, h	e – th, h – th element, surface, node
f	fluid medium
$f\gamma$	fluid phase
i, j, k	indexes of grid nodes
l	liquid phase
o	outside environment
ot	windows
ow	open windows
p	porous medium
$p\gamma$	porous phase
ref	reference value at standard atmospheric pressure, 1.01325·10^5 Pa, and at standard temperature, 273.15 K
res	residual
s	transparent solid medium
sat	at saturation
sky	sky
v	vapor phase
w	water
γ	phase
λ	monochromatic
0	initial value

Greek symbols

α_c	corrective coefficient for evaporative mass flux, dimensionless
β	thermal expansion coefficient, K^{-1}
δ	volumetric transfer coefficient, m^3 s^{-1}
δ_{fo}	volumetric transfer coefficient for forced evaporation, m^3 s^{-1}
δ_{fr}	volumetric transfer coefficient for free evaporation, m^3 s^{-1}
φ	longitude angle, °
γ	water vapor resistance of vegetation, sm^{-1}
η_w	efficiency factor of the windows, dimensionless
$\phi_{p\gamma}$	mass ratio of a phase, dimensionless
λ	wavelength, μm
μ	dynamic viscosity, kg m^{-1} s^{-1}
ν	kinematic viscosity, m^2 s^{-1}
θ	co-latitude angle, °
ρ	phase density, kg m^{-3}
$\bar{\rho}$	medium bulk density, kg m^{-3}
ζ	shape factor, dimensionless
ω	volumetric fraction of a phase, porous medium porosity, m^{3}m^{-3}
Ψ	matric potential, m

Mathematical operators

$\underline{\mathbf{\Phi}}$	typical vector field
ψ	typical scalar field
Δ	difference operator
$\underline{\nabla}$	gradient operator
$\underline{\nabla}\cdot$	divergence operator

control loads, in an unsteady regime. The physical system is geometrically discretized (Fig. 1b) into the following different type of volume elements, with suitable interfaces:

- shell of transparent material, modeled as a solid;
- inside-air, modeled as a multiphase fluid;
- soil, modeled as a multiphase porous medium.