A MODEL FOR RADIATIVE HEAT TRANSFER IN MULTIPHASE MEDIA

J.L. Consalvi, B. Porterie, J.C. Loraud
IUSTI-CNRS umr 6595, 5 rue E. Fermi
Techn. de Château-Gombert,13453 Marseille, cedex 13, France
e-mail:berni@iusti.univ-mrs.fr

Radiative heat transfers in multiphase media is an area of considerable engineering interest. They play an important role in industrial heat processing systems such as coal furnaces or fluidized bed combustors, flying object detectability , atmospheric or environmental problems.

This paper describes a new approach in applying a multiphase formulation to solve the radiation transport equation for an absorbing-emitting-scattering heterogeneous medium. In this approach, a gas phase and N solid phases can coexist in each volume element of the enclosure, which constitute an idealized reproduction of the heterogeneous medium. An averaged directional equation of the radiative intensity is obtained from the local instantaneous equation using the well known formal averaging method of Anderson and Jackson [2]. The averaged form of the radiative transfer equation for a multiphase media may be written in the direction $\mathbf{\Omega}$:

$$\nabla . \left[\alpha_g \left\langle L_g^{\Omega}\right\rangle \mathbf{\Omega}\right] + \sum_{k=1}^{N} \frac{A_k}{4} \left\langle L_g^{\Omega}\right\rangle + \alpha_g \left\langle \beta L_g^{\Omega}\right\rangle = \alpha_g \left\langle (1-\omega)\, \beta L_{g0}^{\Omega}\right\rangle + \sum_{k=1}^{N} \frac{A_k \varepsilon_k}{4} \left\langle L_{k0}^{\Omega}\right\rangle + \frac{\alpha_g}{4\pi} \int_{\tilde{\Omega}=0}^{4\pi} \left\langle \omega \beta L_g^{\tilde{\Omega}}\right\rangle \Phi d\tilde{\Omega} + \sum_{k=1}^{N} \frac{A_k (1-\varepsilon_k)}{16\pi} \int_{\tilde{\Omega}=0}^{4\pi} \left\langle L_g^{\tilde{\Omega}}\right\rangle \Phi_k d\tilde{\Omega} \quad (1)$$

where the subscripts g and k refer to the gas and solid phase quantities, the symbol $\langle\ \rangle$ indicates an average quantity, and L^{Ω}, α_g, β, ω, Φ are respectively the radiative intensity, the gas volume fraction, the extinction coefficient, the albedo and the scattering phase function. The second term of the left-hand side of the multiphase RTE (MRTE) represents the extinction of the intensity due to the absorption and the reflection of the particles whereas, in the right-hand, the second and the last terms represent the emission of the particles and the reflection due to particles. For a solid phase k, we have to define the emissivity ε_k, the volume fraction α_k , and the surface to volume ratio σ_k. The specific surface is then defined by: $A_k = \alpha_k \sigma_k$.

When solving the energy equation of the gas phase, the solution of the MRTE gives the divergence of the radiative flux. This term is the result of the balance between the emission and the absorption by both the gas phase and the solid phases.

$$\nabla . \left[\alpha_g \left\langle \mathbf{q}_g^r \right\rangle\right] = 4\pi\alpha_g \left\langle (1-\omega)\,\beta L_{g0}^{\Omega} \right\rangle - \alpha_g \int_{\Omega=0}^{4\pi} \left\langle (1-\omega)\,\beta L_g^{\Omega} \right\rangle d\Omega + \sum_{k=1}^{N} A_k \varepsilon_k \left(\pi \left\langle L_{k0}^{\Omega} \right\rangle - \frac{1}{4} \int_{\Omega=0}^{4\pi} \left\langle L_g^{\Omega} \right\rangle d\Omega \right) \quad (2)$$

Discrete ordinates solutions of the resulting macroscopic MRTE have been obtained using S4, S6 and S8 approximations and the efficient Variable Weighted Scheme of Lathrop [1].

Our model has been applied to compute radiative heat transfer in a 3D enclosure. Relevant data are presented below:
Enclosure dimensions: $1\ m \times 1\ m \times 1\ m$
Wall temperatures: Firing end: $1000\ K$, others: $300\ K$
Properties of the medium: $\alpha_k = 0.01$, $\varepsilon_k = 0.9$, and $\sigma_k = 3000\ m^{-1}$.
The use of S8 approximation is justified as shown in Fig. 1. A study of the sensitivity of the predictions to the solid phase properties (volume fraction, surface to volume ratio) and radiative properties of each phase of the medium is illustrated in Figs. 2 and 3.

This multiphase radiative heat transfer model has been included in a general multiphase model describing the behavior of a wind-aided fire spreading through a litter of dead pine needles [3]. Test conditions and fuel properties used in the present work are the same as those used for laboratory experiments in a wind tunnel in the open air conducted by Mendes-Lopes *et al.* [4]. The dimensions of the experimental set-up are 4.2 m long and 0.9 m high. The fuel to be burned is distributed uniformly from 1. m to 3.2 m from the left boundary of the computational domain throughout a layer of constant thickness of 0.05 m. For a fuel loading density of 0.5 kg/m^2, a windspeed value of 1 m/s is considered. In accordance with this experimental study, the measured surface-to-volume ratio of the needles is 5511 m^{-1}. Computed results are in good agreement with those obtained from the experiments. In accordance with the observations of Pagni and Peterson [5], it is found that at moderate windspeed, radiation is dominant. Figure 4 shows the time evolution of gas temperature and average radiative intensity.

References

[1] K.D. Lathrop, Spatial differencing of the transport equation: positivity vs. accuracy, *J. Comp. Phys.*, Vol. 4, pp. 475-498, 1969.

[2] T.B. Anderson, R. Jackson, A Fluid Mechanical Description of Fluidized Beds, *Ind. Eng. Chem. Fund.*, vol. 6, pp. 527-539, 1967.

[3] B. Porterie, D. Morvan, J.C. Loraud, and M. Larini, Firespread through fuel beds: modeling of wind-aided fires and induced hydrodynamics, *Phys. of Fluids*, to appear.

[4] J.M.C Mendes-Lopes, J.M.P Ventura, and J.M.P.Amaral, Rate of spread and flame characteristics in a bed of pine needles, *Proceedings of 2nd International Conference on Forest Fire Research*, Luso, Portugal, 1998, edited by D.X.Viegas (ADAI, University of Ciombra, Portugal), pp.497-511.

[5] P.J. Pagni and T.G. Peterson, Flame spread through porous fuels, *Proceedings of the 14th Symp. (Int.) on Combustion*, The Combustion Institute, Pittsburg, PA, 1973, pp. 1099-1107.

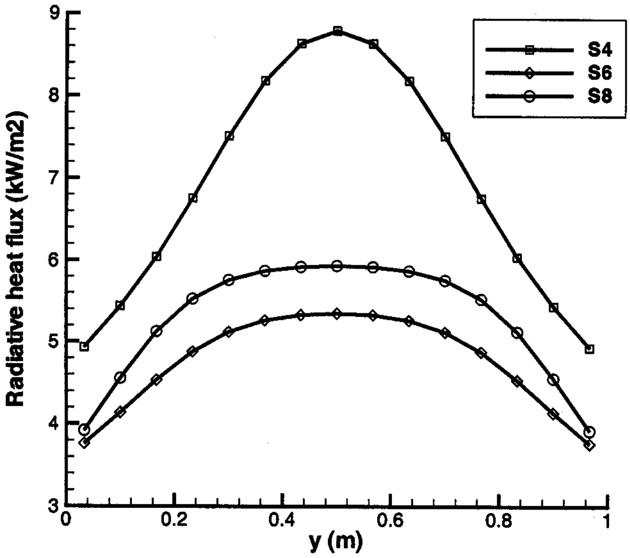

Figure 1: Radiation in a 3D enclosure. Predicted incident radiative flux at the cold wall.

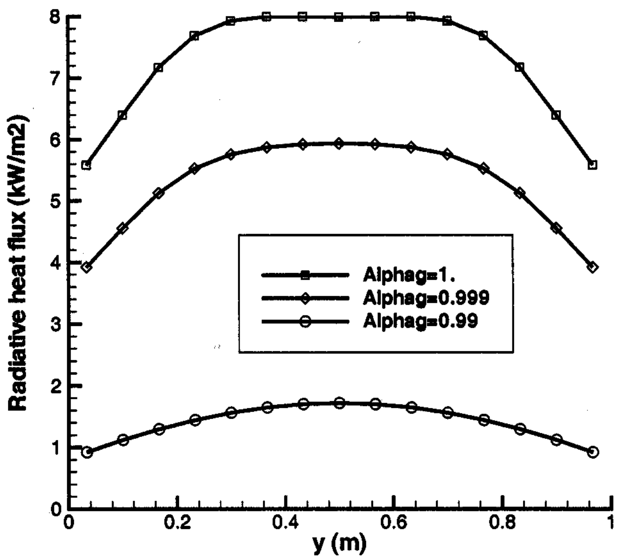

Figure 2: Radiation in a 3D enclosure. Effects of the solid-phase volume fraction on the predicted incident radiative flux at the cold wall. S8-approximation is used.

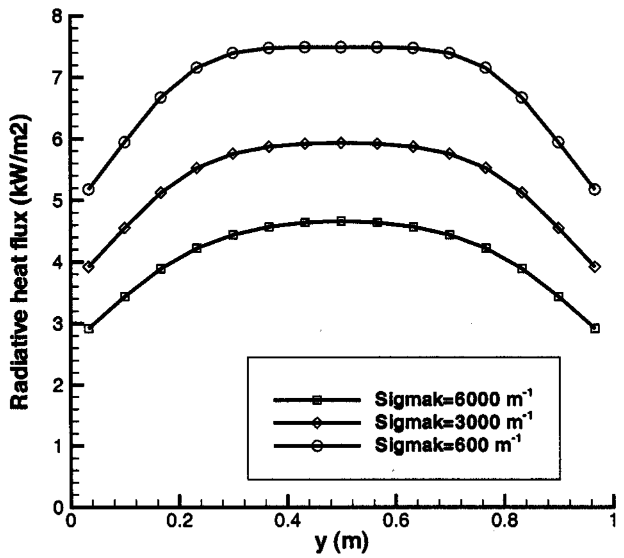

Figure 3: Radiation in a 3D enclosure. Effects of the surface to volume ratio of the solid phase on the predicted incident radiative flux at the cold wall. S8-approximation is used.

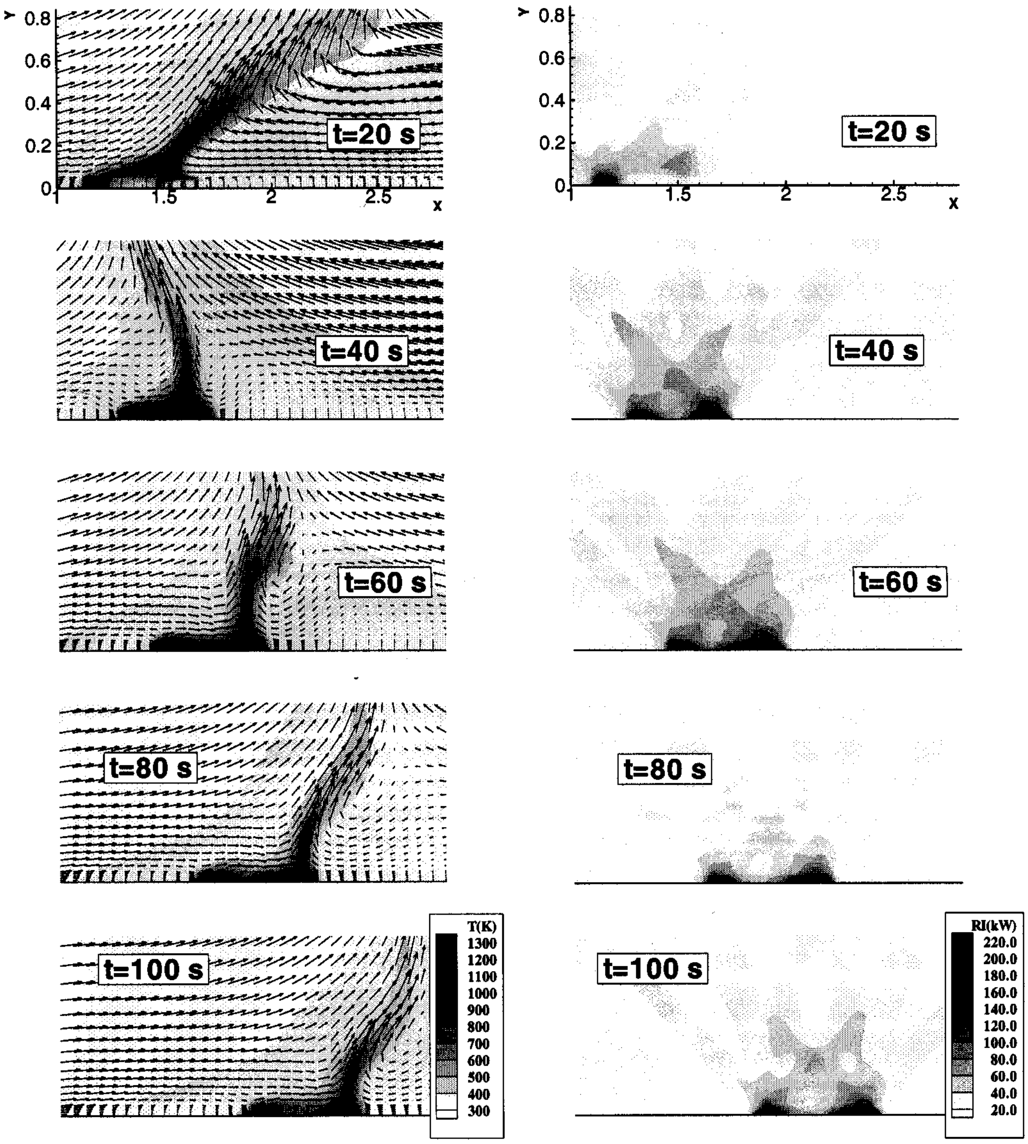

Figure 4: Application of the multiphase radiative model to the spread of a wildland fire under windy conditions. Time evolution of gas temperature and radiative intensity.