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Two-step method for radiative transfer calculations in a developing pool fire at the initial stage of its suppression by a water spray

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ABSTRACT

A procedure based on two-step method is suggested to simplify time-consuming spectral radiative transfer calculations in open flames containing scattering particles. At the first step of the problem solution, the P_1 approximation is used to calculate the divergence of radiative flux, and it is sufficient to determine the flame parameters. The second step of solution is necessary to obtain the radiation field outside the flame, and this can be made independently using the ray-tracing procedure and the transport source function determined at the first step. Such a splitting of the complete problem results in much simpler algorithm than those used traditionally. It has been proved in previous papers that the combined two-step method is sufficiently accurate in diverse engineering applications. At the same time, the computational time decreases in about two orders of magnitude as compared with direct methods. An axisymmetric pool fire at the initial stage of fire suppression by a water spray is considered as the case problem. It is shown that evaporating small water droplets characterised by a strong scattering of infrared radiation are mainly located in regions near the upper front of the flame and one can observe the scattered radiation. This effect can be used in probe experiments for partial validation of transient Computational Fluid Dynamics (CFD) simulations.

1. Introduction

Radiative transfer calculations are the most time-consuming in CFD simulation of fires. Therefore, the use of a simple but sufficiently accurate method for the radiative transfer is critically important to improve the computational costs of CFD codes. A numerical analysis of suppression of fires by water sprays is possible only with the use of spectral models because the optical properties of water droplets cannot be considered on the basis of a gray model [1]. In most cases, there is no need for a very detailed radiation field in CFD calculations. Only the total or integral (over the spectrum) radiative flux divergence is important because this term is needed in the energy equation that couples thermal radiation with other modes of heat transfer. It means that one can consider a differential approach instead of the radiative transfer equation (RTE). Such a choice is really reasonable in the case of combined heat transfer problems including those for fires and combustion systems [1,2]. The P_1 (the first-order approximation of the spherical harmonics method) [1–4] is the simplest method of this type, and there is a very positive long-time experience of using this approach in diverse multi-dimensional problems [1,5–17]. It appears to be sufficiently accurate in the case when one needs only the divergence of radiative flux in the energy equation. Moreover, it was shown in recent paper [18] that the P_1 error is sometimes less than that of the finite-volume method.

It was demonstrated in early papers [19–21] that P_1 approximation may give incorrect values of radiative flux near the boundaries of the computational region in the case of a strong decrease of temperature or extinction coefficient of the medium towards the region boundaries. Unfortunately, this is the case for open flames. Therefore, the second step of the computational radiative transfer model is necessary. This can be done using the transport approximation [12] and a ray-tracing procedure for the RTE with the transport source function determined at the first step of solution. In particular, this combined two-step method presented in papers [5,19,20] was successfully employed in recent paper [17] to calculate radiative heat transfer from supersonic flow with suspended particles to a blunt body.

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Nomenclature

A	area of boundary surface
a	radius of droplet
c	specific heat capacity
D	radiation diffusion coefficient
E	normalized coefficient
f_v	volume fraction of droplets
F	function introduced by Eq. (10)
G	irradiation
g	acceleration of gravity
I	radiation intensity
K	coefficient introduced by Eq. (24b)
k	thermal conductivity
L	latent heat of evaporation
l	coordinate along the ray
m	complex index of refraction
n	index of refraction
Q	efficiency factor
$\vec{q}$	radiative flux
r	radial coordinate
$\vec{r}$	spatial coordinate
S	radiative source function
s	flame thickness along the ray
T	temperature
t	time
u	velocity
x	diffraction parameter
V	volume
W	divergence of radiative flux
z	axial coordinate

Greek symbols

α	absorption coefficient
β	extinction coefficient
γ	coefficient introduced by Eq. (24b)
ε	spectral emissivity
ζ	coefficients in Eq. (25c)
η	dynamic viscosity
k	index of absorption
λ	wavelength of radiation
$\bar{\mu}$	asymmetry factor of scattering
μ_0	cosine of scattering angle
ξ	coefficient in Eq. (25a)
ρ	density
σ	scattering coefficient
τ	optical thickness
χ	functional (9)
Φ	scattering phase function
φ	coefficient introduced by Eq. (25c)
ψ	coefficient introduced by Eq. (24b)
$\vec{\Omega}$	unit vector of direction

Subscripts and superscripts

a	absorption
b	blackbody
cl	cloud
d	droplet
eq	equilibrium
g	gas
j	spectral band number
max	maximum
rel	relaxation
s	scattering
sat	saturation
tr	transport
w	water, wall
λ	spectral
0	initial value

The present study is focused on applicability of the earlier developed combined two-step method to the flames typical of pool fires. The small developing flame just before its suppression by water sprays and also at the initial probe stage of suppression is considered. It should be noted that radiation scattering by evaporating droplets is important even at the beginning of fire suppression and this effect is favourable for the P_1 accuracy because of more smooth angular dependence of the spectral radiation intensity [1].

Following paper [22], we consider infrared radiation outside the absorption band of water to focus on the effect of radiation scattering by water droplets. The simple box model is used for spectral absorption coefficient of molecular gases, but this choice is not critical for the present study because it is focused on a general approach for the radiative transfer calculations and also on infrared scattering by evaporating water droplets outside the absorption bands of water. A numerical solution for the conventional axisymmetric flame (after averaging the numerical results for the 3-D flow field) is considered because this simplification in the flame data is acceptable for the present study.

2. An estimate of the radiation effect on the flow field calculations

The effect of radiation on the flow field of a small developing flame before the flame suppression is considered. The fire scenario for the case problem is based on a 28 cm diameter methane gas flame, burning in the open quiescent environment with a heat release rate of 53 kW. The LES (large eddy simulation) CFD simulation was carried out using an in-house version of FireFOAM code [23], compatible with OpenFOAM version 2.2.x. The combustion sub-model used in this code is based on the Eddy Dissipation Concept (EDC) proposed in paper [24] for RANS (Reynolds-Averaged Navier–Stokes) applications and extended to LES in [25]. The radiative transfer equation is solved using the FVM code, which is open accessible. Gas radiation is treated with the box model approach based on the exponential wide band model to calculate the equivalent band absorption coefficient [26]. The flow field in the present study was computed using FireFoam.

The calculated transient flame is three-dimensional, but deviations of the main parameters from the axisymmetric case are not significant. Therefore, we consider similar axisymmetric fields obtained by an averaging in a selected axial cross section of the real developing flame at $t = 1$ s. A comparison of two temperature fields shown in Fig. 1 indicates that the effect of thermal radiation on the flame formation is relatively small at early stages of flame development. In particular, the maximum temperature in the flame is underestimated by about 1.5% in the calculation without taking into account radiation. Nevertheless, thermal radiation should be taken into account because of its considerable effect on the parameters at the upper "head" of the flame (compare Fig. 1a and b). In light of this observation, rather than using detailed and time-consuming methods for radiative transfer calculations, a much simpler P_1 approximation seems to be reasonable. Of course, the error of this simple approach should be additionally verified to be sure that it is acceptable for the developing flame