International Journal of Heat and Mass Transfer 114 (2017) 664–674

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Evaluation and optimization-based modification of a model for the mean radiative emission in a turbulent non-reactive flow

G.C. Fraga, F.R. Centeno, A.P. Petry, F.H.R. França *

Department of Mechanical Engineering, Federal University of Rio Grande do Sul, Rua Sarmento Leite, 425, 90050-170 Porto Alegre, RS, Brazil

ARTICLE INFO

Article history:
Received 10 March 2017
Received in revised form 8 June 2017
Accepted 9 June 2017

Keywords:
Turbulence-radiation interaction
Radiative emission
Large-eddy simulation
Weighted-sum-of-gray-gases model
Optimization

ABSTRACT

An analysis on turbulence-radiation interaction (TRI) effects and an evaluation and modification of a model for the mean radiative emission are presented, in the context of a non-reactive channel flow of a high temperature homogeneous participating gas. Large-eddy simulation is adopted to generate transient data that can be compared to independent calculations initialized with mean temperature and flow fields. Both the gray gas and the weighted-sum-of-gray-gases models are used to solve the radiative heat transfer, as a means of investigating how the consideration or not of the spectral variation of radiative properties influences TRI effects. Results show an overall small impact of TRI on both the mean radiative heat flux and the mean radiative heat source, but relatively greater effects are observed when the spectral dependence of the problem is not neglected. The model for the radiative emission does not have a good accuracy for the cases studied in this paper, probably because it was developed for higher temperature fluctuation intensities than the range predominant in the simulations. A modification on the values of two coefficients associated with the model, performed based on an optimization methodology, leads to a considerable reduction in the error in the predicted mean radiative heat flux compared to solutions fully neglecting turbulent fluctuations. Although the improvement in the estimation of the mean radiative heat source is not so substantial, in most of the domain this quantity is better predicted with the modified model than without it.

1. Introduction

The numerical coupling of thermal radiation and turbulence is a challenging task even for simple problems, which involves the modeling of instantaneously variating quantities, integrations in time, space, along angular directions and over the whole spectrum of radiation. Moreover, there is a highly nonlinear dependence between fluctuations of radiation intensity and fluctuations of temperature and species concentration. This nonlinear coupling is referred to as turbulence-radiation interaction (TRI), and its importance has been demonstrated experimentally, theoretically and numerically for a number of applications [1]. In some situations, TRI effects can lead to substantial errors when turbulent fluctuations are neglected, i.e., the time-averaged radiation intensity and heat fluxes may differ significantly from those same quantities computed from mean temperature and species concentration profiles [2–4]. Therefore, turbulence-radiation interaction should be accounted for, either by fully or partially solving the turbulent fluctuations, as in direct numerical simulation (DNS) or large-eddy simulation (LES), or by adopting a model capable of representing TRI effects based only on mean quantities, which may be obtained from simpler Reynolds-averaged Navier Stokes (RANS) calculations.

As the conditions of the simulations become more complex, incorporating, for example, the coupled solution of the flow field and the radiative heat transfer, or including chemical reaction effects, computational costs can quickly become prohibitive and a series of compromises must be made in the solution; thus, the necessity of reliable, yet simplified, models increases. Some assumptions are widely accepted and employed for a number of different problems, as the negligence of scattering in the radiative heat transfer solution, and the optically thin fluctuation approximation (OTFA). Of these two, while neglecting scattering is a more general approximation, not limited to studies on TRI, the OTFA is directly related to modeling of terms introduced by turbulent fluctuations. This approximation, proposed by Kabashnikov and Kmit [5], supposes primarily that the correlation between the local spectral radiation intensity and the spectral absorption coefficient is null if the mean free path for radiation is much larger than the inte-

* Corresponding author.
E-mail addresses: guilhermecfraga@ufrgs.br (G.C. Fraga), frcenteno@mecanica.ufrgs.br (F.R. Centeno), adrianep@mecanica.ufrgs.br (A.P. Petry), frfranca@mecanica.ufrgs.br (F.H.R. França).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2017.06.038
0017-9310/

gral turbulence length scale; such assumption greatly simplifies the radiation absorption term and has proven to be valid in a variety of situations [2,6,7].

Although attempts to model other correlations between fluctuating radiative quantities are reported in the literature, none so far has been successful enough outside the cases for which they were designed to be broadly accepted. In [8], a simplified expression for the correlation between the blackbody radiation intensity and the emissivity was proposed (that paper considered only the radiation coming from a surface emitter), by decomposing the instantaneous temperature inside the time-averaged Planck function in mean and fluctuating components and neglecting correlations of odd order. The resulting expression was later adapted for a turbulent participating medium by Snegirev [9], who used experimental data [1] to make further simplifications and model the temperature self-correlation and the absorption-temperature correlation (both components of the mean radiative emission term) as functions of the mean temperature, the temperature variance – that can be solved in the RANS framework through an additional transport equation [10] – and the mean absorption coefficient. With this approximation, the author found good agreement with experimental results for buoyant turbulent flames, employing the Monte Carlo method together with both the gray gas and the weighted-sum-of-gray-gases (WSGG) spectral models to solve the radiative heat transfer part of the problem. After its proposal, a few other studies examined the Snegirev modeling approach for different configurations. In [11], the approximation was tested for turbulent diffusive flames for different turbulence levels through a theoretical analysis based on an assumed-shape probability density function (PDF) of the mixture fraction, also using the gray gas model, resulting in errors of up to 15% for stoichiometric mixtures at higher turbulence intensities when compared to a solution fully including the effects of turbulent fluctuations. Centeno et al. [12], adopted the model for the solution of a non-premixed methane-air flame and reported deviations from experimental data of less than 10% for mean species concentration and mean flame temperature. The same type of flame was investigated in [13], in which the approximation of Snegirev [9] was explicitly formulated in the framework of the WSGG model, obtaining again good agreement with experimental results.

Modeling approaches exclusively for the temperature self-correlation, generally derived from the approximations of Cox [8] and Snegirev [9], were studied or adopted by various authors for different configurations, with mostly positive results [14–17]. Conversely, remaining correlations arising from turbulence-radiation interaction have not been subject to much study, since their contributions are usually less important to the phenomenon. For example, an approximation for the absorption coefficient self-correlation, based on a representation in Taylor series of the functional dependence of the absorption coefficient with temperature, was tested in [11]. The error relative to a solution fully considering turbulent fluctuations was approximately 10% for moderate turbulence levels, but rapidly increased as the turbulence fluctuation got higher.

The present study applies large-eddy simulation (LES) in a low Mach number formulation to firstly assess the importance of TRI in a turbulent non-reacting channel flow of a high temperature homogeneous participating gas; both the weighted-sum-of-gray-gases model and the gray gas model are adopted as a means to investigate how considering or not the spectral variation of radiative properties influences turbulence-radiation interaction effects. Afterwards, the modeling approach of Snegirev [9] for the mean radiative emission, as formulated for the WSGG model by Centeno et al. [13], is evaluated and modified in the framework of the same problem. This modification is proposed following an optimization process based on minimizing the difference between the Snegirev model and the time-averaged radiative emission obtained from the LES computations. As far as the authors' knowledge, this is the first investigation on the performance of the Snegirev approximation employing transient data generated by LES, and also the first study to propose a modification of this approximation based on an optimization methodology. Although other researchers have proposed and utilized modified expressions of the Snegirev approximation, these were based either on theoretical considerations, *ad hoc* corrections or experimental results [14–16].

2. Problem statement

The problem studied consists of a turbulent non-reactive flow of a homogeneous participating gas inside a square duct. Geometry and boundary conditions are similar to [18], and are shown in Fig. 1. The lateral dimensions of the duct are equal to 0.5 m corresponding to a hydraulic diameter D_h (defined by the ratio between four times the cross-sectional area and the wetted perimeter of the cross-section) equal to 0.5 m; the length of the duct is 5.25 m, or $10.5 \times D_h$.

At the front opening of the duct, gas at a spatially uniform and temporally constant temperature of 1200 K is injected with a Reynolds number (based on the hydraulic diameter and the mean bulk velocity) of 5100. Turbulence fluctuations are imposed at the inlet using the Synthetic Eddy Method (SEM) [19], considering a range of turbulence intensities, *IT*, between 0 and 20%. For the remaining parameters necessary for the implementation of the SEM boundary conditions, a constant number of eddies of 1000 and an eddy length scale of 0.1025 m (equal to the hydraulic diameter multiplied by the Von Kármán constant) are used, following sensibility analyses conducted in [19] and by the present authors. The incoming gas, as well as the gas initially inside the computational domain at the start of the simulations, is homogeneous and its composition is either of carbon dioxide or of water vapor – i.e., no dilution with other species is studied (partial pressure equals to 1 atm in all simulations). The other initial conditions are gas temperature of 600 K uniform throughout the domain, null velocity field and pressure equals to atmospheric pressure.

On the opposite surface of the inlet, an open condition to an outside environment kept at atmospheric pressure and composed of the same species as the gas flowing inside the duct is imposed. For the radiative heat transfer calculations, this environment is assumed to behave as a blackbody with a temperature equal to the bulk mean temperature calculated at the cross-sectional plane of grid cells adjacent to the exit surface. The determination of this temperature requires an iterative procedure, updating the outside temperature as equal to the bulk mean temperature computed by the preceding simulation until convergence is reached.

A no-slip condition is imposed at the duct walls. A constant and uniform value of 400 K is prescribed for their temperature; for the

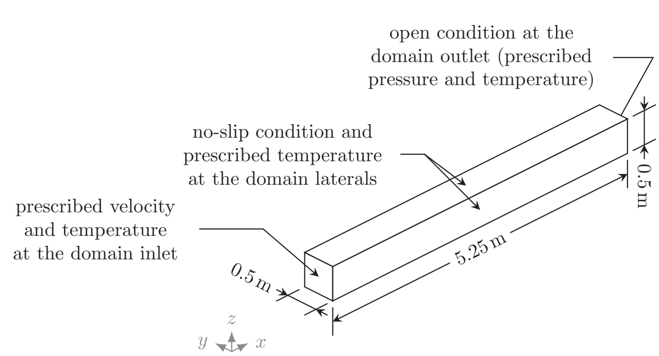

Fig. 1. Geometry and boundary conditions of the problem.