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Coupled radiation and natural convection: Different approaches of the SLW model for a non-gray gas mixture

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Abstract

The coupling between non-gray radiation heat transfer and convection–conduction heat transfer is studied. The spectral line weighted sum of gray gases model (SLW) is used to account for non-gray radiation properties. The aim of this work is to analyze the influence of the different approaches used when calculating the parameters of the SLW model. Such strategies include the use of optimized model coefficients to reduce the number of operations, and the interpolation of the distribution function instead of the use of mathematical correlations. Non-gray calculations are also compared to gray solutions using the Planck mean absorption coefficient, which can be also calculated with the SLW model. The radiative transfer equation (RTE) is solved by means of the discrete ordinates method (DOM). A natural convection driven cavity is chosen to couple radiation and conduction–convection energy transfer. Several cases, with a significant variation of the ratio between radiation to convection heat transfer, as well as the ratio between radiation to conduction heat transfer, are discussed.

Keywords: Non gray media; Radiation; Convection; DOM; SLW

1. Introduction

In the early days of computational fluid dynamics, radiative heat transfer was not taken into account because of the overwhelming amount of computational resources it required. The following, natural step, was to consider only radiative exchange between surfaces, which does not involve the solution of the radiative transfer equation (RTE). As the computational resources increased, detailed numerical models were conceived, such as the discrete ordinates method (DOM), which allowed the resolution of participating media. In the last decade of the last century, feasible, as well as accurate, non-gray radiation models, were formulated. These models can be broadly divided in full spectrum models and band models. The former, which include the weighted sum of gray gases (WSGG) model [1], the absorption distribution function (ADF) model [2], the spectral line weighted sum of gray gases (SLW) model [3], and the full spectrum k-distribution FSK model [4], are

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accurate enough, particularly in homogeneous cases. The later, which include the statistical narrow band (SNB), and the statistical narrow band correlated-k (SNBCK) model [5], are more precise than global models, but far more resource demanding.

The simplest non-gray model ever formulated was the WSGG. Soufiani and Djavdan [6] compared this method to the SNB method for combustion applications. While the WSGG predicted well radiative heat source for a hot medium surrounded by black walls, the absorption by a cold gas of radiation emitted by hot walls was generally underestimated. The authors attributed this discrepancy on total absorption to the fact that the weights in WSGG model were always taken at the temperature of the emitting body.

Belonging to the full spectrum group, both the SLW and ADF models are more precise than the WSGG. For instance, the SLW weights, depend on the local temperature and could lead to more accurate predictions. Coelho et al. [7] used the SLW model to account for turbulence–radiation interaction in a diffusion flame. The inclusion of non-gray radiative properties improved the agreement between the computed and the measured data. Soufiani et al. [8] employed the ADF model for a mixed laminar convection case, considering an homogeneous gas mixture. Their conclusion was that, by taking radiation into account, the flow is affected significantly.

The newest full-spectrum model, up to the author's knowledge, is the FSK, a rigorous mathematical improvement of the SLW method. Essentially, a reordering of the wavenumber integration is performed, and a integration over absorption coefficient (instead of an integration over wavenumber) is performed. This is the same principle on which the SLW is based, but in the FSK formulation, highly efficient quadrature methods can be used to carry out the wavenumber integration. In the case of scalable absorption coefficient, this method yields exact results, affected only by numerical errors. The FSK model has approximately the same computational cost of the SLW model, once an exhaustive data preprocessing has been completed.

On the other hand, band models are more accurate than full spectrum, or global, models. Liu et al. used the SNBCK model for a methane/air [9] flame. In this flame, which can be considered optically thin, it turns out that radiation model did not have much influence in the outcome. Coelho [10] also used a correlated-k band model, this time with a prescribed temperature and concentration fields, obtained from experimental measures. The works by Liu et al. [9] and Coelho [10], however, pointed out that turbulence and combustion models may have greater influence in the final result than the non-gray radiation model for coupled problems. Soufiani et al. [11] also used a correlated-k model to solve a forced convection situation, considering pure gases only. In their work, preheating or precooling of the gas in the entrance of a circular duct due to radiation was studied. Comparison with the ADF model showed that for the precooling condition the ADF performs well, while bigger differences between the band and the global models were obtained for higher temperatures.

Among the different non-gray models mentioned above, the SLW model stands out for its simplicity of its formulation, its level of accuracy, and for the low (compared to band models) computational resources it requires. The aim of this work is to analyze the performance and implementation of the SLW model in detail. When considering a non-gray model, the SLW in our case, one realizes that there are plenty of strategies that can be adopted. There are several databases with absorption line data which can be used, one may opt for use fitted distribution functions or calculated ones, one may use high resolution partitions of the absorption coefficient domains or optimized coefficients. All of these factors possibly have an impact on the results, which may, or may not, be significant. If radiation is not the only mode of heat transfer, this significance can be different whether radiation is globally meaningful or not.

In order to study the impact of these different approaches of the SLW model, this work presents the numerical analysis performed in a thermal driven cavity where the coupling of non-gray radiation and convection is taken into account: first, by varying the convective contribution, and second, by considering two cases, one of which is radiation dominated and the other where radiation and conduction are roughly equally significant. These calculations are compared to gray solutions, to stress the appropriateness of the use of the non-gray SLW model, with the different approaches detailed in Section 2.3.

2. Mathematical model

We consider a non-reactive, steady state mixture of gases in order to study the influence of the SLW model parameters on a complex problem, which combines also convection and conduction heat transfer. The mixture