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Symbolic Monte Carlo methods for analysis of radiative transfer in high-temperature heterogeneous materials

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1. Introduction

Extensive researches are today devoted to analysis and characterization of radiative transfer in high-temperature porous materials. For instance, radiative transfer may have a significant impact on the performance of ceramic thermal barrier coating for jet-engine applications [1]. In order to evaluate radiative transfer, the knowledge of the heterogeneous materials radiative properties at high-temperature is required. Indeed, radiative properties (such as the absorption and scattering coefficients, and the phase function) of porous ceramics are strongly dependent on temperature. It is therefore relevant to identify radiative properties of the considered materials at their operating temperature.

At ambient temperature, spectral measurements of bi-directional or directional-hemispheric transmitted and reflected fluxes have been used to identify radiative properties of materials [2]. However, at high-temperature, the emission becomes predominant, and developing experimental bench for such measurements remains a challenging issue at high-temperature. In this context, an experimental bench has been specifically designed for measuring spectrometric emission of high-temperature materials heated from 800K up to 2000K in [1]. The approach proposed in [1] is to identify radiative properties at high-temperature from those emission measurements using the radiative transfer equation (RTE) as radiation model.

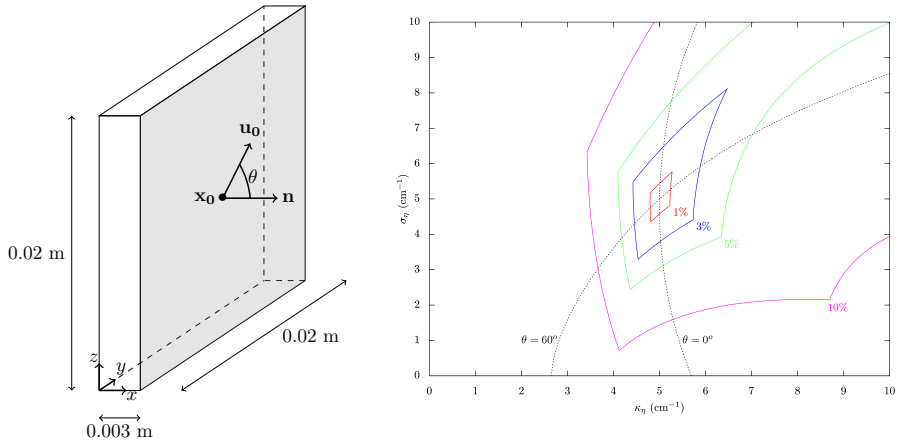
Two questions remain from this work: in which case it is possible to identify radiative properties using the RTE as model, and which measurements are most relevant to obtain information about radiative properties of the considered material. In this study, we propose to develop symbolic Monte Carlo methods (SMC) in order to give elements of analysis for answering the preceding questions.

2. Symbolic Monte Carlo methods (SMC)

A symbolic approach has been proposed recently in order to express radiative quantities as polynomials of the absorption and scattering coefficients [3]. SMC and standard Monte Carlo (MC) methods are very similar. In SMC, some parameters are retained as symbolic variables, while in standard MC scalars values are affected to all parameters. Consequently, SMC outputs the radiative quantities as a function of the symbolic parameters, while standard MC outputs numerical values. In [3], it is shown that using null-collision algorithm [4], SMC outputs the radiative quantities Q_R (such as the radiative intensity, the radiative source term, or the radiative heat fluxes) as simple bivariate polynomial of the absorption κ and scattering σ coefficients:

$$Q_R(\kappa,\sigma) = \sum_i \sum_j a_{ij} \kappa^i \sigma^j \tag{1}$$

One single SMC allows to estimate all values of the polynomial coefficients a_{ij}, $\forall i$ and $\forall j$. From this simple polynomial form, the radiative quantity can be estimated for a large range of parameters values in agreement with the RTE model. It is therefore very effcient for inverse analysis, since all possible solution of the RTE are given over the parameter space [5]. The method benefits from all advantages inherent to standard MC: it remains a reference method since the statistical errors are estimated with



(a) Test case (b) Experimental error influence

Figure 1: Influence of the experimental error on the space of possible couple solution of the identification

the standard deviation, and it is adapted to complex configurations (real geometries with scattering and reflexion phenomena).

Moreover, using such SMC polynomial expressions allows to develop uncertainty quantification analysis very easily. For instance, Fig. 1b illustrate the influence of the experimental error over the possible couple of absorption κ_η and scattering σ_η coefficients that are solution of the RTE model and corresponds to particular measurements of the radiative intensity. In figure 1b, pseudo-measurements of radiative intensity emitted by a sample of high temperature material has been assumed (see figure 1a). The pseudo-measured values results from a medium with $\kappa_\eta = 5$ and $\sigma_\eta = 5$ cm^{-1}. The radiative intensity has been pseudo-measured (by direct calculation) in two directions, for $\theta = 0$ and $\theta = 60°$.

In the case of 1% of experimental error, the identification of the absorption and scattering coefficient can be achieved with a relatively good accuracy using those measurements (possible solution are inside the red line: $\kappa_\eta \in [4.8, 5.2]$ and $\sigma_\eta \in [4.2, 5.8]$), while in the case of 5% or 10%, the space of possible couple of $(\kappa_\eta, \sigma_\eta)$ that can leads to the measured valued of the radiative intensities is infinite. The identification is therefore impossible ith these experimental errors.

In conlusion, SMC allows to gather very practical information about the feasibility of the inversion. It can guide experimental design, giving information about which measurements are relevant for the considered problem. Moreover, it allows to determine which model is the most suitable to characterize the radiative properties from given measurements.

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