Radiative Heat Transfer Modeling in Fibrous Porous Media

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Phenolic-Impregnated Carbon Ablator (PICA) was developed at NASA Ames Research Center as a lightweight thermal protection system material for successful atmospheric entries. The objective of the current work is to compute the effective radiative conductivity of fibrous porous media, such as preforms used to make PICA, to enable the efficient design of materials that can meet the thermal performance goals of forthcoming space exploration missions.

**Background**

National Aeronautics and Space Administration

**Methods**

An efficient and MPI parallel procedure is developed to first obtain relevant view-factors using a collision based Monte-Carlo method and second to compute the final steady-state radiative heat flux [1]. The radiative conductivity computed can be combined with the value calculated for thermal conductivity using PuMA [2], a NASA software for extracting porous material properties, to determine the total effective conductivity from the intrinsic conductivity of constituting phases.

\[ q'' = -[k_c + k_r] \nabla T \]

**Finding the View Factors**

The view factor, \( F_{ij} \), between surfaces \( i \) and \( j \), where \( A_i \) and \( A_j \) are the areas of the surfaces, are defined in the equation below. A View Factor equal to zero implies that two surfaces cannot “see” each other, or in other words, a light ray emitted by one of the surfaces cannot reach the other surface.

**Method:** The input geometry is first triangulated into discrete surfaces. For each surface \( i \):

1. A large number of rays are projected outward to uniformly sample the angular space near the surface.
2. Each voxel passed through by a ray is interrogated to see if it contains any emitting surfaces for which to calculate the corresponding view factor, using the equation below.
3. Lastly, when all rays for surface \( i \) are processed, another surface is chosen and steps 1-3 are repeated.

\[ F_{ij} = \frac{1}{A_i A_j} \int_{A_i} \int_{A_j} \frac{\hat{n}_i \cdot \hat{n}_j}{|\hat{n}_i| |\hat{n}_j|} dA_i dA_j \]

**Heat Transfer Calculation**

The view factors data generated is used calculate the radiative heat transfer in a certain domain. The radially outward total heat flux leaving a surface, is computed with the equation below. As this constitutes a large sparse coupled linear system, an iterative process is used to solve for the radiosity of each surface between walls 1 and 2:

\[ J_i = \varepsilon_i \sigma T_i^4 + (1 - \varepsilon_i) \sum_j F_{ij} J_j \]

where \( \varepsilon \) is emissivity and \( T \) the local temperature. This computation assumes that each surface is isothermal, diffuse, and opaque. The output is the net axial heat flux, averaged over the other two directions.

**Results**

Using two different values for the carbon conductivity, corresponding to TC2 and TC2 heat treated at 2500°C, the total thermal conductivity of FiberForm in N\(_2\) is computed using PuMA.

**Conclusions**

The dataset of radiosity, which is computed at each voxel, is first cleared of outliers, which are the void voxels, then filtered using a robust least squares fitting method. The effectiveness of the radiosity at the two ends of the domain as well as the temperature difference imposed between them, are used to compute the effective conductivity.

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