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Development Of A Unified Numerical Model For Ceramic Foams

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Porous materials or foams have been utilized in a wide range of applications due to superior properties compared to their solid bulk counterparts, such as large surface area, lightweight, good mechanical strength and chemical resistance [1]. Open-cell foams have found use in high-temperature applications like solar receivers, thermal energy storage, and heat exchangers [2]. Porous structures pose a challenge to numerical modeling due to complexity and randomness. Numerous numerical models have been created to simulate fluid flow and heat transmission in foams at the pore and macro levels [3]. These models include coupling of fluid dynamics, heat transfer, and radiation transport. However, severe temperature gradients may be induced when the foams are exposed to high temperature conditions leading to extreme stresses and subsequent structure failure [4]. Therefore, it is necessary to combine structural behavior with thermo-hydraulic behavior in order to evaluate the potential failure scenarios and ensure the safety and reliability of porous foams working at high temperatures.

The main objective of the current work is to develop a comprehensive three-dimensional numerical model that couples flow physics, heat transfer, radiation transport and mechanical behavior of porous foams exposed to high heat fluxes that imitate concentrated solar radiation. In the current study, a porous cylindrical Silicon Carbide foam is used, with air acting as the heat transfer fluid. In order to employ volume-averaged governing equations, the porous foam is assumed to be a homogenous continuum media. The flow physics is modeled with Brinkmann equations considering a laminar and compressible steady-state flow. The local thermal non-equilibrium model is considered for energy transport, including distinct energy conservation equations in fluid and solid phases [5]. The two energy equations are coupled via a volumetric convective source term [6]. The radiation transport is solved only in the solid phase considering it as an absorbing, emitting and isotropically scattering medium, while air is assumed transparent to radiation. The radiative transfer equation in the solid phase is solved using the discrete ordinates method. The porous foam is modeled mechanically as a non-deformable linear elastic material. [7]. The Gibson-Ashby model is used to scale down the mechanical properties of the solid bulk SiC to that of foam [8]. The boundary conditions for the mechanical model are set such that stresses are generated only due to thermal effects, while mechanical effects are assumed negligible. In order to investigate the structural failure, the Rankine criterion is implemented considering the brittle nature of SiC foam.

The mathematical problem is set up in finite element based software COMSOL Multiphysics®, and validation studies are performed to verify the software capability in solving various physics. The developed numerical model is applied in parametric studies to investigate the effects of different structural, design, and operational parameters on the hydrodynamic, thermal and structural behavior of the foam.

keywords: porous media, heat transfer, numerical modeling, thermo-mechanical coupling

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