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Macroscopic foam model with effective material properties for high heat load applications

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ABSTRACT

Macroscopic equations are a practical tool for numerical modeling of physical processes in components based on porous media. In this study a set of macroscopic equations is presented including the effective material properties to model the fluid dynamics and heat transfer in open porous metallic foams in high heat load applications. The model is validated in a test campaign using a high radiation flux test facility. In addition the model is used to assess the potential of open porous metallic slip-reaction-foams based on a high temperature resistant nickel alloy in the application as effusion cooled combustion chamber wall elements. The analysis shows promising results even though the cooling efficiency has not yet reached a satisfying level.

1. Introduction

Due to the high surface to volume ratio and its permeability open porous materials are used in many industrial applications to transfer heat from a solid phase to a fluid phase [1–3]. One application under investigation is effusion cooling of combustion chamber walls in modern gas turbines [4]. The term effusion cooling is contradictorily used in literature. Here, effusion cooling is used for a concept, where the cooling fluid passes through a porous wall without undergoing a phase change. In Fig. 1 a sketch of a simplified combustion chamber with porous wall elements is shown.

Within an interdisciplinary research project (SFB 561) of the Deutsche Forschungsgemeinschaft (DFG) several advanced concepts for the design of a combined cycle power plant were studied aiming at a collective increase of the overall power plant efficiency from 58% to 65% [5]. One of these concepts is the application of metallic foams as effusion cooled combustion chamber wall elements. In this context a simple and cost efficient production method named slip-reaction-foam-sinter-(SRFS)-process was developed for the fabrication of open porous metallic foams [6,7]. Due to its high temperature resistance the nickel alloy INCONEL 625 was selected as base material [8].

The formation of two pore classes is characteristic of these slip-reaction-(SR)-foams. Large primary pores with diameters in the range of 0.1–1 mm result from hydrogen out-gassing during the foaming process. Smaller secondary pores can be found in the matrix material surrounding the primary pores. The typical size of the secondary pores is about 10 μm. The combination of the two pore classes determines the foam topology. Large primary pores built an open network surrounded by a matrix structure, which is porous itself. In Fig. 2 a section of an SR-foam is displayed, clearly showing the different orders of magnitude between the pore classes. For the analysis of the pore distribution and geometry porosimetry and optical means are used.

Simulations based on numerical models describing the underlying physical mechanisms are well established for the layout of functional components. In the case of porous media the structure is often irregular and complex. Components consisting of such porous material are typically orders of magnitude bigger than the details of the porous structure. This leads to a prohibitive computational effort for direct pore level simulations of the components. Nevertheless direct pore level simulations of parts of the porous components are subject of current research and its limits are continuously shifted towards larger and more complex structures [9–12]. At the moment the method of choice to deal with the complexity of porous media and the resulting computational efforts is the use of macroscopic equations. These equations describe the behavior of the porous material on a macroscopic scale omitting the detailed representation of the porous network. The macroscopic equations can be obtained theoretically starting from the heat and mass transfer at pore level for representative volumes and using the volume averaging method. A detailed description of

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