International Journal of Thermal Sciences 123 (2018) 86–98

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

journal homepage: www.elsevier.com/locate/ijts

CFD modeling of convective scalar transport in a macroporous material for drying applications

Sreeyuth Lal [a, b, c, *], Francesco Lucci [d], Thijs Defraeye [a], Lily D. Poulikakos [e], Manfred N. Partl [e], Dominique Derome [a], Jan Carmeliet [a, f]

[a] *Laboratory for Multiscale Studies in Building Physics, Empa, Swiss Federal Laboratories for Materials Science and Technology, Überlandstrasse 129, CH-8600 Dübendorf, Switzerland*
[b] *Department of Civil, Environmental and Geomatic Engineering, ETH Zürich, CH-8093 Zürich, Switzerland*
[c] *Electrochemistry Laboratory, Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland*
[d] *Laboratory of I. C. Engines, Empa, Swiss Federal Laboratories for Materials Science and Technology, Überlandstrasse 129, CH-8600 Dübendorf, Switzerland*
[e] *Road Engineering/Sealing Components Laboratory, Empa, Swiss Federal Laboratories for Materials Science and Technology, Überlandstrasse 129, CH-8600 Dübendorf, Switzerland*
[f] *Chair of Building Physics, ETH Zürich, CH-8093 Zürich, Switzerland*

ARTICLE INFO

Article history:
Received 23 December 2016
Received in revised form
14 June 2017
Accepted 11 September 2017
Available online 22 September 2017

Keywords:
Convective drying
Porous media
Porous asphalt
Computational fluid dynamics

ABSTRACT

Convective drying is one of the most important forms of moisture removal in macroporous materials exposed to environmental loads. In this study, the influence of airflow on the convective removal of water vapor (passive scalar) from porous asphalt (PA), a macroporous material, is investigated for different wind speeds and levels of liquid water height within the material, using computational fluid dynamics (CFD). The PA domain for the CFD simulations is reconstructed from three-dimensional X-ray micro-computed tomography images. Steady Reynolds-averaged Navier-Stokes (RANS) k-ε model with low Reynolds number modeling for the near-wall region is used for the turbulence modeling. Simulations are carried out for three wind speeds, 0.1, 1.5 and 10 m/s, and three depths of the scalar (vapor) source, 0.13, 15 and 29 mm, within the specimen. Only the highest wind speed has a clear influence on the total vapor flux measured at the interface. Additionally, at the highest wind speed, air entrainment in pores near the air-material interface plays an important role in vapor removal. At lower wind speeds, diffusion within the material is the dominant vapor transport mechanism. At a wind speed of 10 m/s, strong vortices are observed which inhibit vapor removal in cavity-type pores by recirculating vapor within the pore. However, at the same wind speed, vapor transport in a non-cavity-type pore system is found to be very strong due to strong air convection.

1. Introduction

The durability of several porous materials which are constantly exposed to environmental loads, such as concrete, sandstone, limestone, brick, asphalt etc., is highly dependent on the residence time of liquid water within them as water is one of the main agents of degradation [1–5]. Moreover, the residence time of moisture in soil and its accurate modeling thereof [6] is important for groundwater management and agriculture. One of the most influential environmental factors that determine the residence time of water in such porous media is airflow. Airflow enhances drying in microporous media (defined here as materials with pore sizes smaller than 0.1 mm) primarily by affecting the air boundary layer at the air-material interface. However, in macroporous media (pore sizes larger than 0.1 mm), momentum exchange between air and water vapor in the large pores at the interface, due to air entrainment, can additionally influence the drying process. A detailed investigation of such air entrainment in macroporous media and its effect on the drying process is missing in literature.

Porous asphalt (PA) is a macroporous medium with pore sizes ranging from micrometers to millimeters. Its durability is particularly sensitive to the residence time of water in it. PA is

---

[*] Corresponding author. Laboratory for Multiscale Studies in Building Physics, Empa, Swiss Federal Laboratories for Materials Science and Technology, Überlandstrasse 129, CH-8600 Dübendorf, Switzerland.

E-mail address: sreeyuth.lal@psi.ch (S. Lal).

https://doi.org/10.1016/j.ijthermalsci.2017.09.010
1290-0729/

used as the surface layer of roads for drainage of water and thereby for preventing aquaplaning and splash-spray effects during and after rain events. PA has a porosity of approximately 20% and is a composite material made from fine and coarse mineral aggregates, a bituminous binder and air voids. Due to its high permeability, a large area of the internal structure of PA is exposed to water during a rain event. Although most of the water within PA drains due to gravity, some residual water remains as corner films in hydrophilic pores and as bulk liquid in dead-end pores. The drying of this residual liquid content is influenced by various factors such as wind, solar radiation and vehicular loads causing a pumping action within the pores. The focus of this study is on the influence of wind on drying of PA. In a previous experimental study [7], boundary layer characterization of airflow above full-scale PA slabs was performed using particle imaging velocimetry (PIV). However, the phenomenon of air entrainment in PA was not observed in the PIV measurements of [7] as only the flow field above 5 mm from the air-material interface was measured with PIV. Neutron radiography (NR) investigations of convective drying in PA [8] documented the spatial and temporal evolution of moisture content in PA under controlled airflow. Although the influence of airflow on convective drying in PA was visible in the aforementioned NR experiments, the exact mechanism by which airflow influenced drying in PA i.e. through affecting the boundary layer alone or also through air entrainment, could not be determined from the experiments.

Convective drying in porous media can be studied with various approaches. In particular, numerical models such as pore network models [9,10] and continuum models [11] are used to couple heat, air and moisture (HAM) transport within a porous medium to the external heat and moisture transfer taking place at the surface of the medium that is open to the environment. Increasingly, computational fluid dynamics (CFD) is also used to study the interaction of airflow with porous media during drying [12–16]. In these studies, the porous medium domain is either represented as a continuum with well-defined macroscopic transport properties or as an assembly of idealized shapes. As an example of the latter case, Sun & Hu [17] analyzed heat and mass transfer in porous foods by representing the fibrous medium as hexagonal tubes. However, heat transfer by convection is neglected in their study. For the computational domain for CFD simulations, the use of a real porous material geometry is more realistic. Such actual geometries are often reconstructed from three-dimensional imaging techniques such as microcomputed tomography (μ-CT). Although there are a few CFD studies in areas such as biophysical modeling where the computational domain is generated from μ-CT scans [18–20], no similar studies for porous asphalt exposed to the environment exist. A comprehensive understanding of airflow at the air-material interface will provide insights about the complexity with which this airflow and the macroporous material should be modeled for convective drying simulations using any of the methods previously mentioned i.e. pore network models, HAM models etc.

In this study, convective removal of water vapor from PA is investigated using CFD. The PA domain used in the simulations is extracted from a three-dimensional X-ray μ-CT scan. The influence of two parameters on convective vapor removal from PA are investigated in this study: wind speed and the depth of the vapor source within the material i.e. the water level within PA. The effect of air entrainment on vapor removal is also studied. The effect of these parameters on convective vapor removal is quantitatively analyzed by monitoring the proportion of convective flux compared to the total vapor flux at the air-material interface.

2. Materials and methods

2.1. Material properties

The PA specimen used in this study is a PA11 specimen that has a nominal maximum aggregate size of 11 mm. The pore structure of the PA11 specimen is imaged with the X-ray μ-CT setup of Empa. The setup consists of an X-ray source (X-ray tube ″XT9225-TEP″, Viscom), an XYZ linear stage (composed of three linear stages ″LS-270″, Micos) for positioning the specimen, a rotation table (″UPR-160 F air″, Micos) and an X-ray detector (″XRD 1621 CN3ES″, Perkin-Elmer). The PA11 specimen is mounted at a distance of 503.2 mm from the X-ray source and 467 mm from the detector. From a pixel size of 200 μm and a geometrical magnification of $\sim$1.9, a spatial resolution of 103.7 μm is obtained in the final 3D dataset. The chosen tube parameters are an acceleration voltage of 200 kV and a nominal current of 100 μA. In order to reduce artefacts, the X-ray spectrum is hardened with a 1 mm Cu filter. For each scan, a region of interest of 1000 × 2000 pixels is chosen due to the elongated geometry of the specimen. 720 radiographs are recorded with a total integration time of 10 s per image from different viewing angles distributed over 360° in 0.5° steps. The X-ray detector is calibrated before the start of the measurement and therefore no additional dark and flat field corrections are necessary. After ring and beam hardening artefact corrections, the three-dimensional spatial distribution of the attenuation coefficient is calculated by an in-house Feldkamp code [21].

In this study, a PA11 specimen of dimensions 180 mm × 10 mm × 30 mm is used. In Fig. 1, a visible light photograph (a), X-ray μ-CT slices at specimen thickness of 1 mm (b), 5 mm (c), and 9 mm (d), and two-dimensional cumulative porosity distribution (CPD) obtained from reconstructions of 3D X-ray μ-CT scans (e), are shown. In Fig. 1 (e), the black regions represent the presence of an aggregate along the entire thickness of the specimen i.e. the porosity is 0, and the white regions represent the presence of a pore space along the entire thickness of the specimen i.e. the porosity is 1. Intermediate grey values represent porosities between 0 and 1 along the specimen thickness. For obtaining an insight into the pore sizes in the PA11 specimen, the binary X-ray μ-CT scans of the specimen is converted into a simplified pore network of large spheres (pores) connected to each other by smaller spheres (throats). This pore network is extracted from the X-ray μ-CT images using the modified maximal ball algorithm of [22], which is an extension of the work of [23]. The maximal ball (MB) algorithm works by fitting the largest possible spheres, centered on each air voxel, such that they just touch the solid boundary. Spheres that are completely inscribed within other spheres are removed and the remaining spheres are called maximal balls, where the largest maximal balls are considered as pores and the smaller balls between them are considered as throats. Fig. 2 presents the pore size distribution (PSD) and throat size distribution (TSD) of the PA11 specimen as estimated by the MB algorithm. Large pore sizes in the order of millimeters can be observed in Fig. 2. Both PSD and TSD show a unimodal distribution with means of 1.2 mm and 0.4 mm respectively. The wide range of distribution of PSD and TSD gives a first indication of a well-connected pore space.

2.2. Numerical model and computational domain

Two sets of CFD simulations are carried out in this study. The first set of simulations (precursor simulations) are two-dimensional simulations to assess the performance of the chosen air turbulence model. The second set of simulations (PA simulations) are three-dimensional simulations performed to carry out the objectives of this study i.e. analyze air and vapor (i.e. scalar)