Experimental Thermal and Fluid Science 74 (2016) 390–403

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

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

Turbulent airflow above a full-scale macroporous material: Boundary layer characterization and conditional statistical analysis

Sreeyuth Lal [a,b,*], Peter Moonen [c,g], Lily D. Poulikakos [d], Manfred N. Partl [d,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 Zurich, CH-8093 Zurich, Switzerland
[c] Laboratoire des Fluides Complexes et leurs Réservoirs (UMR 5150), Université de Pau et des Pays de l'Adour (UPPA), BP 1155, 64013 Pau Cedex, France
[d] Laboratory for Road Engineering/Sealing Components, Empa, Swiss Federal Laboratories for Materials Science and Technology, Überlandstrasse 129, CH-8600 Dübendorf, Switzerland
[e] Division of Highway and Railway Engineering, KTH Stockholm, S-10044 Stockholm, Sweden
[f] Chair of Building Physics, ETH Zürich, CH-8093 Zurich, Switzerland
[g] Pau Centre for X-ray Imaging (UMS 3360), Université de Pau et des Pays de l'Adour (UPPA), BP 1155, 64013 Pau Cedex, France

ARTICLE INFO

Article history:
Received 20 August 2015
Received in revised form 25 November 2015
Accepted 6 January 2016
Available online 14 January 2016

Keywords:
Turbulence
Conditional sampling
Macroporous
Porous asphalt
Wind tunnel
PIV

ABSTRACT

Convective drying of macroporous materials is governed by the complex interaction between airflow above and into the material, the roughness of the air–material interface and the characteristics of the material pore system. In this study, we experimentally investigate this interplay in detail and at full-scale, using porous asphalt (PA) as a model material. The characteristics of the turbulent flow in the immediate vicinity of the material surface are studied with full-scale wind tunnel experiments at three flow speeds over two types of PA with different surface porosities and surface pore sizes, and are compared to similar measurements over a smooth and impermeable reference material. It is shown that, above a certain wall-normal distance, turbulence profiles can be scaled to make them independent of the flow speed. However, at low speed, the scaling breaks down due to a combination of organized turbulent structures of high intensity and a low turbulence background. No generally valid scaling applicable at all tested air speeds is found close to the surface, where drying occurs. Hence, realistic drying experiments must be performed at full scale and for the entire range of velocities of interest.

1. Introduction

Turbulent airflow over porous media can be observed in a variety of materials ranging from those that are exposed to airflow in the atmosphere, such as bricks, concrete, soil, rocks, and asphalt, to those that are subjected to forced airflow in industrial drying processes, such as fruits, paper pulp, and wood. The drying cycles within these materials are significantly influenced by the turbulent airflow over them. In microporous materials like bricks, rocks and concrete, convective drying is accelerated by the enhanced turbulence induced by porosity near the air–material interface, which increases the air–water vapor mixing at the interface. In a macroporous material, such as porous asphalt, drying is further accelerated by air penetration into the macro-pores connected to the surface. The former phenomena, i.e. turbulence in the near-wall region of rough surfaces, has been experimentally and numerically investigated by considering a combined free flow-porous media domain [32,4,6,23,25]. The latter phenomenon, i.e. fluid penetration into macro-porous media, has been studied using refractive-index matching techniques [26,35]. A different but related effect is flow-through drying [24] in which a gas phase injected into a wet porous medium immiscibly displaces the liquid, followed by the evaporation of the liquid into the gas phase. A macroporous material, due to the considerable air penetration into its internal structure, will display a complex drying process resulting from the interaction of all the aforementioned mechanisms.

Porous asphalt (PA), a material characterized by interconnected pores of sizes ranging from µm to mm, is a material in which forced convective drying is expected to be an important mechanism of moisture removal. PA has a porosity of approximately 20% and is used as a surface layer on roads. It is a composite material made principally from coarse mineral aggregates and a bituminous binder. It features enhanced water drainage and acoustic

* Corresponding author at: Laboratory for Multiscale Studies in Building Physics, Empa, Swiss Federal Laboratories for Materials Science and Technology, Überlandstrasse 129, CH-8600 Dübendorf, Switzerland. Tel.: +41 58 765 6533; fax: +41 58 765 1122.

E-mail address: Sreeyuth.lal@empa.ch (S. Lal).

http://dx.doi.org/10.1016/j.expthermflusci.2016.01.005
0894-1777/

absorption properties compared to classical dense graded mix asphalt. However, the durability of PA is found to be significantly lower than dense graded mixtures due to the high exposure of its internal structure to water after large rain events. Water primarily affects the binder–aggregate adhesion in PA and therefore leads to its accelerated deterioration [29]. Analyzing the residence time of water in PA after large rain events is therefore important for designing longer-lasting PA surface layers. Although gravity-driven drainage is expected to be the most important water loss mechanism, the contribution of forced convective drying near the top surface is expected to be non-negligible. Boundary layers over porous surfaces tend to be more turbulent than those above impermeable rough surfaces [42]. Therefore, analyzing the turbulent boundary layer above PA is important in the context of studying convective drying of PA by wind.

Turbulent wind boundary layers over rough surfaces have been extensively studied in the past [39,36,34]. From these studies, it was determined that the structure of the turbulent boundary layer primarily depends on the air speed and surface roughness. However, turbulence structures in the near-wall region and the effects of porous structures on turbulence are still not well understood [15]. Recent studies towards this end have been carried out by Suga et al. [37], Suga and Kuwata [38] and Iida et al. [15]. However, these studies considered either simplified porous media (using ribs or tubes) or restricted the fluid flow region to narrow channels, for analyzing the effect of those flows on the heat and/or momentum transfers in catalyst surfaces, heat exchangers and fuel cells. Full-scale investigations of airflow above large porous media such as soil and asphalt have not yet been published, to the best of our knowledge, despite the application of wind tunnels to study phenomena such as soil erosion [13,12]. It should be noted that although the general velocity field near large structures can be captured by scaled-down wind tunnel experiments using Reynolds analogy, several flow characteristics are not proportional to the size of the model and thus cannot be extrapolated directly from such experiments [22].

In light of all these studies, the focus of this study is on the turbulence in the near-wall region of a real macroporous medium, namely porous asphalt. Thus, the objective of the present work is a statistical investigation of the turbulent boundary layer above PA surfaces of different surface porosities. To that end, we perform a full-scale study of airflow above two different types of PA pavements and compare it to a quasi-smooth surface. We characterize the flow field by means of Particle Image Velocimetry (PIV). The turbulence statistics employed in this study are based mainly on previous studies on turbulent boundary layers over (impermeable) rough walls [1,3,34]. To our best knowledge, our study is the first application of these statistics to characterize the flow over a macroporous surface. We use conditional sampling techniques to assess the contribution of organized flow structures to the overall turbulence.

First, the experimental setup and the porous materials used in this study are described. Thereafter a statistical analysis of the turbulence observed above PA is performed, followed by a detailed analysis of those parameters that are relevant for forced convective drying.

2. Methods and materials

2.1. Wind tunnel and PIV system

The experiments were performed at the ETH-EMPA wind tunnel in a closed-loop configuration. A schematic layout of the experimental setup is shown in Fig. 1. A large slab of porous asphalt (2400 mm $\times$ 400 mm $\times$ 30 mm) was placed in the wind tunnel. The slab was flush-mounted by adding an extruded polystyrene board around it and a smooth fairing upstream to avoid boundary layer separation. After the installation of the model, the test section had a free cross-section of 1900 mm $\times$ 1050 mm. Special care was taken during the installation so that no damage was experienced by the samples.

The PIV system consisted of two CMOS cameras (LaVision GmbH, 12-bit dynamic range, 2016 $\times$ 2016 pixels), mounted side-by-side to obtain a total field of view (FOV) of 280 mm $\times$ 140 mm. The airflow was seeded by means of spherical Di-Ethyl-Hexyl-Sebacat (DEHS) particles with a narrow size distribution around an average diameter of 1 μm. The seeding was done with a 5-nozzle particle generator placed just before the honeycombs and screens. After the seeding process, a sufficient time was allowed for the particles to be uniformly distributed in the entire wind tunnel and this was verified through preliminary images. A Nd:YLF laser with a power of 30 mJ/pulse was used to illuminate the DEHS particles within the field of view. The vertical plane of the laser sheet was parallel with the airflow direction and centered along the asphalt slab (Fig. 1(b)). For each experimental run, 3155 statistically independent image pairs were acquired at a frequency of 10 Hz, which was estimated from the integral time scale. Best practice guidelines for PIV [17,7,31] were taken into account to minimize the errors of the measurements. 3155 image pairs corresponded to a full camera memory and allowed the calculation of the mean properties of the flow. The acquired images were first pre-processed by subtracting the background light intensity. Both images of each pair were cross-correlated following a three-level multi-pass approach, starting from a coarse interrogation window of 48 $\times$ 48 pixels up to a fine interrogation window of 24 $\times$ 24 pixels, with an overlap of 50% for all the passes. Between the passes, a median filter was applied to remove or replace vectors whose difference from the root mean square (rms) value of the neighbor signal was more than 10 times the standard deviation of the neighboring rms value. The final vector resolution achieved was 0.9 mm. Due to considerable reflection of the laser from the asphalt surface, the lowest measured vector was at 5 mm above the surface. Measurements were conducted at three different free-stream air velocities i.e. 1, 2.85 and 4.75 m/s to allow verification of Reynolds independency of the observed quantities. The measurement window was at a distance of 1540 mm from the leading edge of the specimen. This distance was found to be sufficient to obtain fully developed velocity profiles in the measurement window.

2.2. Material description

Porous asphalt (PA) is a road surface material primarily composed of coarse aggregates held together by a bituminous binder. The interconnected pore space is typically 20% of the overall volume. Several additives like polymers, cellulose fibers etc. can be added to the bitumen to enhance the overall structural integrity of PA. A detailed description of the micro-structure of PA is given in Lal et al. [20]. In this study, two types of porous asphalt are used, namely PA8 and PA11, which differ by their maximum aggregate sizes (Table 1) and thereby have different surface porosities at the near-wall region. In Table 1, the results from a sieve analysis of the aggregates are shown for both types of asphalt. Each number corresponds to the relative contribution of the mass of aggregates in the corresponding size range to the total mass of all aggregates. It can be observed that, in PA8, most aggregates are in the 4–8 mm size range, while in PA11 most aggregates are in the 8–11.2 mm size range. Due to the larger aggregate sizes of PA11, the pore sizes are larger in PA11. Therefore, PA11 is characterized by larger pores per unit length. This can be appreciated from the photographs of the top and side surfaces of PA8 and PA11, shown in Fig. 2.