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

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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's 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 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.

Keywords: turbulence; conditional sampling; macroporous; porous asphalt; wind tunnel; PIV

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, asphalt etc., to those that are subjected to forced airflow in industrial drying processes, such as fruits, paper pulp, wood etc. 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 (Prinos, Sofialidis, and Keramaris 2003; Agelinchab et al. 2006; Arthur et al. 2009; Liu, Chen, and Wang 2013; Narasimhan, Raju, and Chakravarthy 2014). The latter phenomenon, i.e. fluid penetration into macro-porous media, has been studied using refractive-index matching techniques (Northrup et al. 1991, Saleh et al. 1992). A different but related effect is flow-through drying (Mahadevan, Sharma, and Yortsis 2006) 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 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 (Poulikakos and Partl 2012). 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 (Zippe and Graf 1983). 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 (Townsend 1976; Schlichting and Gersten 2000; Raupach, Antonia, and Rajagopalan 1991). 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 (Iida et al. 2014). Recent studies towards this end have been carried out by Suga et al. 2013, Suga and Kuwata 2014 and Iida et al. 2014. 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 (Gillette 1978, Gabriels et al. 1997). It should be noted that although the general velocity field near large structures can be captured by scaled-down wind tunnel experiment using Reynolds analogy, several flow characteristics are not proportional to the size of the model and thus cannot be extrapolated directly from such experiments (B. Liu et al. 2014).

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 porosity. 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 (Adrian et al. 1989; Adrian

1996; Raupach, Antonia, and Rajagopalan 1991). 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 the 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.

Figure 1: Schematic of the experimental setup: (a) side view and (b) top view. All measurements are in *mm*. FOV = field of view.

The PIV system consisted of two CMOS cameras (LaVision GmbH, 12-bit dynamic range, 2016×2016 pixels), mounted side-by-side to obtain a total field of view (FOV) of 280 mm × 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 μ m. 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 (Keane and Adrian 1990; Bolinder 1999; Prasad 2002) 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 48×48 pixels up to a fine interrogation window of 24×24 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. 2014. 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 porosity 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.

Fig. 2(e) depicts the evolution of porosity (ratio of pore area to aggregate area) as a function of depth from the surface. The porosity profiles are calculated from X-ray microcomputer tomography (X-ray μ CT) scans with a spatial resolution of 200 μ m for two PA8 and PA11 specimens of dimensions 80 mm $\times$ 80 mm $\times$ 30 mm. These specimens were compacted in a similar way as those for the wind tunnel tests and hence their pore structures are expected to be similar. From fig. 2(e), it is clear that near the surface, larger pore sizes in PA11 do not lead to larger overall porosity.

Due to the interconnected nature of large pores near the surface of a typical PA specimen, as shown in a previous study (Poulikakos et al. 2013), a roughness height that is representative of the entire specimen, as for nonporous rough surfaces, cannot be estimated. As mentioned in Section 2.1, the PA slabs used in this experiment are of dimensions 2400 mm $\times$ 400 mm $\times$ 30 mm. It is to be noted that the depth of an actual PA pavement is also approximately 30 mm. The orientation of slabs within the wind tunnel can be clearly seen in fig. 1. The slabs were freshly prepared specifically for these experiments.

In addition to measurements on PA, measurements are also conducted over extruded polystyrene boards, henceforth referred to as foam boards. The measurements over foam boards are used as a base-

line case since foam is impenetrable and has a much lower roughness than that of PA, thereby making it a quasi-smooth surface. For the measurements over foam boards, the PA slab was simply replaced by a slab of foam of similar dimensions.

Table 1: Aggregate size distributions of the specimens

Sieve size (mm)	Mass-%	
	PA8	PA11
0 - 0.063	4	4
0.063 - 0.125	1	1
0.125 - 0.25	2	1
0.25 - 0.5	2	1
0.5 - 1	2	2.5
1.0 - 2.0	4	2
2.0 - 4.0	6	4.5
4.0 - 5.6	38	7
5.6 - 8.0	38	7
8.0 - 11.2	3	60
11.2 - 16.0	0	10

Figure 2: Photographs of a section of the PA specimens: (a) top view and (b) side view of a section of the PA8 specimen, (c) top view and (d) side view of a section of the PA11 specimen and (e) porosity as a function of material height.

3. Results and discussion

3.1 Uncertainty in the estimation of statistical quantities

The relative error in the estimation of mean air speed from N statistically independent images can be estimated as:

$$\varepsilon_{\mu} = \frac{Z_c \cdot TI}{\sqrt{N}}, \quad (1)$$

where Z_c is the confidence coefficient, which is equal to 1.96 for a confidence level of 95%, and TI is the turbulence intensity, defined as:

$$TI = \frac{\sqrt{rms(u')^2 + rms(v')^2}}{\langle U \rangle}, \quad (2)$$

where u' and v' are velocity fluctuations in the streamwise and wall-normal directions respectively and $\langle U \rangle$ is the mean air speed defined as:

$$\langle U \rangle = \frac{1}{N} \sum_{i=1}^N U_i, \quad (3)$$

where U_i is the instantaneous streamwise velocity.

The relative error in the standard deviation is estimated as:

$$\varepsilon_{\sigma} = \frac{Z_c}{\sqrt{N}}. \quad (4)$$

The maximum uncertainty of the mean and standard deviations within each experiment in this study is given in Table 2. As expected, the maximum uncertainty in mean air speed is at the near-wall location for all experiments i.e. at $y=5 \text{ mm}$. However, due to the high number of sampling images used in this study, it can be seen that even the maximum uncertainties are below 2% and 2.5 % for the mean and standard deviations respectively.

3.2 Mean and turbulent statistics

In this section, the airflow measurements over the three different surfaces i.e. foam board (smooth), PA8 and PA11, at three different speeds i.e. 1 m/s (low speed, $Re_{\theta} = 700$), 2.85 m/s (moderate speed,

$Re_\theta = 2900$) and 4.75 m/s (high speed, $Re_\theta \approx 4200$) are studied. It should be noted that air speeds are classified into low, moderate and high in this study solely for better readability and this does not imply a strict classification for scaling. For details about the calculation of Re_θ , the Reynolds number based on momentum thickness, the reader is referred to the discussion on Table 2. Figure 3 shows the mean air speed, $\langle U \rangle$, as a function of the normal distance from the wall, y , for the different cases. As expected, we observe at each considered air speed that a boundary layer develops due to the interaction with the surface. The boundary layer is more clearly distinguishable at high air speeds. At low speed, the effect of surface porosity on the velocity profiles is less pronounced. At moderate and high speeds, the effect can be seen up to $y = 60 \text{ mm}$. At high speed, a small effect of the difference in surface porosity between the two types of PAs is visible in the airflow velocity profiles. This aspect will be investigated in more detail in the subsequent sections.

Figure 3: Vertical profiles of mean streamwise velocity.

Figure 4: Vertical profiles of mean streamwise velocity, scaled by friction velocity for (a) Foam, (b) PA8 and (c) PA11.

Figure 4 shows the same profiles as fig. 3 after normalization. In this figure, the mean air speed is replaced by the non-dimensional mean air speed $U^+ = \langle U \rangle / u_*$, and the vertical coordinate by the non-dimensional height above the surface $y^+ = y \cdot u_* / \nu$, where u_* is the friction velocity and ν is the kinematic viscosity of air. The normalized profiles theoretically follow the so-called roughness-modified law-of-the-wall within the logarithmic layer (i.e. $y^+ < 30$), which is given by:

$$U^+ = \frac{1}{\kappa} \log y^+ + B - \Delta U^+, \quad (5)$$

where κ is the Von Karman constant, $B = 5.2$ and ΔU^+ is the roughness function (Clauser 1954). By comparing the velocity profiles on the same surface, the roughness function is taken out of the equation. The friction velocity u_* can then be estimated by minimizing the difference between the law-of-the-wall and the measured mean velocity profiles in the logarithmic layer. The calculated friction velocities for all the cases are listed in Table 2 and are used later in this study to scale the turbulence parameters.

Table 2: Boundary layer parameters

Surface	Free-stream velocity U_∞ (m/s)	Boundary layer height δ (mm)	Displacement thickness δ^* (mm)	Momentum thickness θ (mm)	Shape factor SF (-)	Friction velocity u_* (m/s)	Reynolds number Re_θ (-)	$\varepsilon_{\mu,\max}$ (%)	$\varepsilon_{\sigma,\max}$ (%)
Foam	1.00	107.8	13.9	11.0	1.3	0.048	0.7×10^3	1.92	2.47
	2.85	115.1	22.0	16.5	1.3	0.110	2.9×10^3	0.85	2.47
	4.75	112.4	19.9	15.2	1.3	0.171	4.3×10^3	0.70	2.47
PA8	1.00	125.1	14.4	11.7	1.2	0.050	0.7×10^3	1.59	2.47
	2.85	131.4	22.3	16.6	1.3	0.110	2.9×10^3	0.63	2.47
	4.75	126.9	20.1	15.0	1.3	0.168	4.3×10^3	0.48	2.47
PA11	1.00	115.1	15.2	12.1	1.3	0.049	0.7×10^3	1.76	2.47
	2.85	132.3	22.6	16.7	1.4	0.106	2.9×10^3	0.59	2.49
	4.75	125.1	19.7	14.7	1.3	0.164	4.2×10^3	0.56	2.47

In Table 2, various other boundary layer parameters are listed. The first parameter of interest is the boundary layer height, δ , which is the height at which 99% of the free-stream velocity, U_∞ , is reached (see fig. 5). Above the boundary layer height, the mean air speed remains approximately constant and below that, a boundary layer profile is found. Based on fig. 3, the boundary layer height seems to exceed the field of view for the moderate and high-speed measurements. However, as the velocity observed at the top of the field of view (i.e. at $y = 140$ mm) is close to the free-stream velocity, measured by a pitot-tube positioned in the free stream, we make the assumption that $U_\infty = U|_{y=140\text{mm}}$ for these cases. The impact of this assumption on all derived parameters was evaluated by a sensitivity study (see Appendix). Although Schlichting and Gersten (2000) observed a decrease in the boundary layer height with increasing air speed as $\delta \propto U_\infty^{-1/5}$, the results from this study indicate the existence of a critical Reynolds number below which this inverse proportionality breaks down. This is similar to the results of Paterna (2015), who found an unexpectedly low boundary layer height at low speed ($Re_\theta = 1500$) and attributed this to a high degree of organization in the flow. Prior to investigating this hypothesis, we ensure that the obtained trend is not a product of the method used to determine the boundary layer thickness. Therefore, in Table 2, two related yet more robust quantities are calculated, namely the displacement thickness, δ^* , and the momentum thickness, θ (Coles 1956, Schlichting, Gersten, and Gersten 2000). These parameters are defined as:

$$\delta^* = \int_0^{\infty} \left(1 - \frac{U}{U_{\infty}}\right) dy, \quad (6)$$

$$\theta = \int_0^{\infty} \frac{U}{U_{\infty}} \left(1 - \frac{U}{U_{\infty}}\right) dy. \quad (7)$$

The displacement thickness can be interpreted as the distance by which an inviscid flow has to be displaced in wall-normal direction to account for the drop in velocity within the boundary layer in a real fluid. Similarly, the momentum thickness can be thought of as the distance by which an inviscid outer flow has to be displaced in a wall-normal direction to give the same lower momentum that exists in the boundary layer in a real fluid. These two parameters are illustrated in fig. 5. The ratio of the displacement thickness to the momentum thickness is called the shape factor, $SF = \delta^*/\theta$, which is also given in Table 2. The final parameter in the table is the Reynolds number based on the momentum thickness, $Re_{\theta} = U_{\infty}\theta/\nu$, which is used to characterize the different air speed regimes.

Figure 5: Analogous representation of boundary layer parameters in a real flow to a hypothetical inviscid flow to obtain robust parameters such as (a) displacement thickness and (b) momentum thickness.

Analogous to the boundary layer height, δ^* and θ are expected to decrease with increasing Reynolds number. However, from Table 2, it can be observed that this is not the case for any of the surfaces. In other words, the low-speed measurements have an unusually low boundary layer thickness. This anomaly is reflected in the shape factor SF as well and could be due to the occurrence of organized

turbulent structures at low air speeds (Adrian, Meinhart, and Tomkins 2000, Paterna 2015). We return to this hypothesis in the subsequent paragraphs.

Figure 6: Skewness profile of u (left) and v (right) at the three air speeds

Figure 6 shows the skewness profiles, $\langle S_q \rangle$, of the streamwise velocity component, u , and the wall-normal velocity component, v . Skewness is the time-averaged third-order moment defined as:

$$\langle S_q \rangle = \frac{\frac{1}{N} \sum_{n=1}^N [q_n(r, t) - \langle q(r, t) \rangle]^3}{\left\{ \sqrt{\frac{1}{N} \sum_{n=1}^N [q_n(r, t) - \langle q(r, t) \rangle]^2} \right\}^3}, \quad (8)$$

where $q_n(r, t)$ is a spatially (r) and temporally (t) instantaneous quantity, $\langle q_n(r, t) \rangle$ is the time-averaged quantity and N is the total number of time steps. The skewness of a Gaussian distribution is zero. A positive skewness points to a large number of excursions with higher values than the mean while a negative skewness points to a large number of excursions with lower values than the mean.

Unlike the velocity profiles in fig. 3, the third order moments reveal surface porosity-induced differences for all considered air speeds. An important observation from fig. 6 is that in the near-wall region, only the low-speed measurements show positive skewness of u and v . A positive skewness near the wall reflects the presence of high shear events imposed on a background of lower turbulence (Johansson and Alfredsson 1982; Fernholz 1994). This could explain the low values found for the displacement and momentum thickness in the low speed (and low turbulence) measurements (see Table 2). In the near-wall region, high positive values of the skewness of streamwise velocity, $\langle S_u \rangle$, are found only in the low-speed measurements, indicating the dominance of sweep events at this speed. This observation is further strengthened from the results of the Q-H analysis (see Section 3.3). Due to the higher magnitude of u compared to v , $\langle S_u \rangle$ gives more insight into the dynamics of turbulent flows than $\langle S_v \rangle$. For the moderate and high-speed measurements, the general trend is that the skewness changes from negative to positive along the wall-normal direction. This points to the dominance of events with velocities lower than the average velocity, near the surface. This is expected due to the low airflow velocity in the inner layer of the boundary layer. However, this is not the case with the low-speed measurements, where the dominance of events with velocities higher than the average velocity can be observed, near the surface. This is yet another indication of a small boundary layer thickness, which was already observed from Table 2. It can also be observed that, with increasing velocity, the skewness profiles of the different surfaces overlap more. Reading this together with fig. 3, it can be observed that, while the differences in the velocity profiles of the three surfaces increase with increasing air speed, the skewness profiles increasingly converge with increasing air speed. This could be due to the fact that the relative magnitude of the increase in velocity fluctuations is small compared to the increase in mean air speed.

Figure 7 presents the three measured time-averaged Reynolds stress components i.e. the shear stress $\langle u'v' \rangle$, streamwise turbulence $\langle u'u' \rangle$ and wall-normal turbulence $\langle v'v' \rangle$, as a function of the distance from the wall. No scaling is applied in this figure. For the low speed flow, the Reynolds stresses are low and the profiles above all the surfaces share a similar shape except very close to the wall. At the moderate speed, the profiles above the two PA surfaces are similar, though they are slight-

ly different from those above foam. At the highest speed, a clear dependency of the profiles on the surface porosity can be observed, especially close to the surface. Furthermore, at high air speed, the maximum Reynolds stress is found at a different height for the three surfaces. The peaks in shear stress and streamwise turbulence for the two PA surfaces are vertically separated at the highest speed by at least 10 mm, as can be seen in figs. 7(a) and 7(b). Finally, high-speed flow generates significantly more turbulence over the surface of PA11 than over PA8. In the low and moderate-speed measurements, though a difference in the turbulence plots can be observed between the smooth surface and the PA surface, there is no appreciable difference between the two PA surfaces.

Figure 7: Profiles of Reynolds stress components without scaling: (a) Shear stress, (b) Streamwise turbulence and (c) Wall-normal turbulence.

Figures 8 and 9 present the Reynolds stress components in inner velocity scaling (normalized with u_*) and outer velocity scaling (normalized with U_∞), respectively. In inner scaling, Reynolds independence of both shear and streamwise Reynolds stress components (figs. 8(a) and 8(b)) can be observed for the moderate and high speed cases for $y > 80$ mm and for the wall-normal component (fig 8(c)) at all heights. The same observations hold in outer scaling, but from $y > 50$ mm onwards (fig 9).

Figure 8: Profiles of Reynolds stress components in inner scaling: (a) Shear stress, (b) Streamwise turbulence and (c) Wall-normal turbulence.

Figure 9: Profiles of Reynolds stress components in outer scaling: (a) Shear stress, (b) Streamwise turbulence and (c) Wall-normal turbulence.

The fact that no generally valid scaling was found has important practical implications for future experiments that study forced convective drying of wet porous asphalt. The presence of strong, organized turbulent structures near the wall during the low-speed measurements could be the reason why the boundary layer velocity profiles at the low speed do not show similarity with the moderate and

high-speed profiles after scaling. This aspect is examined in further detail in the next section. Scaling laws are found to be valid for the moderate and high speed flows, but only above a certain height. This is not surprising. The scaling of turbulence parameters has always been a challenge for researchers, which has led to a variety of inner-outer mixed scalings, especially in and around the near-wall region. Energy balance of the boundary layer indicates that the total power dissipated by the boundary layer scales on the free-stream velocity and shear stress, while the shear stress in turn scales on the friction velocity (De Graaff and Eaton 2000). Thus, the total rate of energy depends by the turbulence depends on both free-stream velocity (used for outer scaling) and friction velocity (used for inner scaling).

To sum up, for all the air speeds considered in this study, no generally valid scaling was found close to the surface, where drying occurs. Hence, studies of drying would require performing experiments at full-scale and for the entire range of velocities, similar to the experiments reported in this paper. This is all the more important since low speed flows (< 2.85 m/s) are a common occurrence over land surfaces (Archer and Jacobson 2005) and we observed distinctive turbulence profiles at the lowest speed. In this context, it should be noted that a generally valid velocity scaling, even if it were observed, does not imply a scalable drying behavior in a macro-porous material like PA since air penetration into the material should also be taken into account.

3.3 Conditional sampling

It is now widely accepted that downdraft motion (sweeps) and updraft motion (ejections) of air are the most important constitutive events occurring in turbulent airflow near a rough surface. These events are the most important contributors to the Reynolds stresses and momentum transfer near the air-material interface. Conditional statistics, such as Quadrant-Hole (Q-H) analysis, are often used to study such turbulent structures in the flow near a fluid-solid interface (Wang, Salewski, and Sundén 2010; Longo, Domínguez, and Valiani 2015). In this section, Q-H analysis is used to investigate the contribution of coherent motions such as sweeps and ejections in the turbulent flow (Willmarth and Lu 1972; Raupach 1981). The shear stresses are conditionally-averaged to distinguish between the contributions of “organized” and “unorganized” events to the total turbulence. Based on the signs of the instantaneous velocity fluctuations of the streamwise and wall-normal velocity components, u' and v'

respectively, the events can be classified as Q1 events ($u' > 0$, $v' > 0$), Q2 events ($u' < 0$, $v' > 0$), Q3 events ($u' < 0$, $v' < 0$) and Q4 events ($u' > 0$, $v' < 0$), according to the quadrants in which these points fall in a $u' - v'$ diagram, as shown in fig. 10(b). The Q2 events are ejections while the Q4 events are sweeps. The most important events fall in quadrants 2 and 4 since these events give positive instantaneous contributions ($-u'v'$) to the Reynolds stress (Guo et al. 2010). Ejections and sweeps (fig. 10(a)) are assumed to be associated with organized structures, responsible for significant transfer of momentum between the surface and the air (Willmarth and Lu 1972). Despite the possible importance of such coherent motions for forced convective drying of soil or porous asphalt surfaces, no study has been reported on them to the best of our knowledge.

Figure 10: (a) Schematic representation and (b) graphical representation of sweeps and ejections

In order to introduce a notion of scale, the time-averaged contribution of each quadrant i , $\langle u'v' \rangle_{i,H}$, can be filtered to exclude fluctuations with a magnitude smaller than the size of the hyperbolic hole H :

$$\langle u'v' \rangle_{i,H} = \lim_{T \rightarrow \infty} \frac{1}{T} \int_0^T u'(t)v'(t) I_{i,H} [u'(t)v'(t)] dt, \quad (9)$$

where $I_{i,H}$ is a binary variable that is used to select the events to include, and which implicitly accounts for the minimum shear stress that should be considered:

$$I_{i,H} [u'(t)v'(t)] = \begin{cases} 1 & \forall (u', v') \in Q_i; |u'v'|_{i,H} \geq H \sqrt{\langle u'^2 \rangle} \sqrt{\langle v'^2 \rangle} \\ 0 & \text{otherwise} \end{cases} \quad (10)$$

By varying H , the contributions of eddies with different scales can be analyzed and their impact on the relative importance of the individual quadrants can be recognized.

Figures 11, 12 and 13 present the results of the Q-H analysis on foam, PA8 and PA11 respectively, scaled by friction velocity i.e. inner velocity scaling. Subplots ‘a’, ‘d’, ‘g’ concern the low-speed measurements, subplots ‘b’, ‘e’, ‘h’ the moderate-speed measurements and subplots ‘c’, ‘f’, ‘i’ the high-speed measurements. Three different values of the hyperbolic hole are considered for the analysis i.e. $H = 0, 2$ and 4 . It can be observed that generally, ejections (Q2) and sweeps (Q4) dominate over the Q1 and Q3 events. Among ejections and sweeps, sweeps are more dominant, especially at the low-speed measurements. Above all surfaces, at $H = 2$, the contributions from Q1 and Q3 events fall to almost zero. The high intensity of Q2 and Q4 events close to the wall in the low-speed measurements confirms the hypothesized presence of organized structures based on the low displacement and momentum thicknesses in Table 2 and the positive skewness near the surface in fig. 6(a) and 6(b).

Figure 11: Q-H analysis on foam board with inner velocity scaling, where Q2: ejections and Q4: sweeps.

Figure 12: Q-H analysis on PA8 with inner velocity scaling, where Q2: ejections and Q4: sweeps.

Figure 13: Q-H analysis on PA11 with inner velocity scaling, where Q2: ejections and Q4: sweeps.

As the value of H increases, the overall dominance of sweeps over ejections increases. Specifically for the moderate and high-speed plots of both PAs, the location of the Q2 and Q4 peaks shifts further from the wall with increasing value of H , and also the breadths of the peak widen. This shows that the effect of strong sweep and ejection events is felt across a much larger distance from the wall along the wall-normal direction as compared to that of the weak ones. In other words, the stronger the intensity of the sweeps and ejections, the lesser the probability that the momentum transfer from these organized structures will be restricted to the surface region. On the two PA surfaces, at the moderate and high velocities, the intensities of sweeps and ejections are similar in the near-wall region. Along the wall-normal direction, the gap between them widens in favor of sweeps. This clear trend can also be seen in the measurements on foam, but to a lesser extent. Near a perfectly smooth surface, ejections are the dominant events while sweeps are the dominant events near a rough surface (Keirsbulck et al. 2002). This can be the reason why sweeps are still dominant near the smoother foam surface, but not as dominant as they are near the rougher PA surfaces.

Figure 14: Comparison of Q2 (ejection) and Q4 (sweep) events between the three surfaces at $H = 4$.

Figure 14 presents the comparison between the three surfaces in terms of the sweeps and ejection events for the three considered air speeds. Only the results for $H = 4$ are compared. The wall similarity

hypothesis states that outside the roughness sublayer, the turbulent motions are independent from the wall roughness, as confirmed by Perry, Schofield, and Joubert (1969); Raupach (1981); and Raupach, Antonia, and Rajagopalan (1991). The effect of surface roughness on the sweep and ejection events can indeed be observed only up to a certain wall-normal distance. From the moderate and high-speed measurements, it can be observed that this distance is approximately $y = 70 \text{ mm}$ and $y = 100 \text{ mm}$ for the ejections and sweeps respectively. Significantly, very close to the surface, a clear difference in the profiles of PA8 and PA11 can be seen only in fig. 14(c). This is consistent with the inferences made from figs. 7-9, i.e. a difference in drying behavior of the two PAs, as a consequence of their different surface porosity, is expected to be prominent only at air speeds equal to or higher than 4.75 m/s. This has an important implication for future studies to model convective drying of PAs with different surface porosity. If the air speed is equal to or lower than 3 m/s, a uniform turbulent boundary layer can be assumed near all the PA surfaces, as long as their surface porosity and the pore profiles on the surface are not very different from those of PA8 and PA11. In this context, a detailed quantification of the surface porosity of the different types of PAs would be an ideal complement to the present study.

In fig. 14(d)-(f), the surface with the maximum porosity i.e. PA11, is not always the one with the strongest sweeps. This contradicts the observations of Keirsbulck et al. (2002) who observed strong sweeps on rough surfaces. In fact, for the low-speed measurements, the sweep events are even the strongest on the smooth surface (foam), as seen in fig. 14(d). However, as the speed increases, the sweep events on the rougher surfaces gain strength and at high speed (fig. 14(f)), the roughest surface (PA11) has the strongest sweep events. A high fluctuation in the v -component of velocity facilitates stronger sweep events (Krogstad, Antonia, and Browne 1992). Therefore, higher air speeds, due to higher turbulence, and rougher surfaces, due to the reduced damping of the v -component by the cavities, should lead to more dominant sweep events. While the measurements in Keirsbulck et al. (2002) were done at $Re_\theta = 8500$, the high-speed measurements in this study are at $Re_\theta = 4300$. This could explain why the observations of Keirsbulck et al. (2002) are not applicable to the low and moderate velocity measurements in this study, since the wall-normal turbulence is too low at these speeds. Additionally, this also points to the existence of a critical Reynolds number $2900 < Re_\theta < 4300$ above

which the difference in the surface porosity of PA pavements influences the presence of organized structures in the near-wall region.

4 Conclusions

The mean and turbulent flow characteristics of airflow above macroporous surfaces are analyzed in this study. Airflow over two types of porous asphalt (PA) pavements is studied at three air speeds at constant temperature. Measurements over foam boards (quasi-smooth surface) are used as a base to which the measurements over the rougher PA pavements are compared. The most important conclusions are:

1. At low air speed, the small values of the displacement and momentum boundary layer thicknesses indicate the presence of organized turbulent structures, which is confirmed by the positive skewness of the streamwise velocity component in the near-wall region. Moreover, in the Q-H analysis, a high intensity of ejection (Q2) and sweep (Q4) events is also observed in the near-wall region in the low-speed measurements.
2. The effect of strong sweeps and ejections is observed across a significant distance along the wall-normal direction above the macroporous PA-surfaces. As the distance from the wall increases, the difference between the intensities of sweep and ejection events also increases, with sweeps dominating ejections. This implies that as the distance from the wall increases, the occurrence of high-speed air from regions far from the wall dominates the arrival of low-speed air from the wall.
3. For the moderate and high-speed measurements, a sensitivity of sweep and ejection events to surface porosity is observed but only within the first 80 and 100 mm respectively above the surface. Within these heights and at these velocities, the sensitivity of sweeps to surface porosity is more pronounced than that of ejections. However, no clear dominance of either sweeps or ejections on any particular surface is observed, although sweep events over more porous surfaces gained strength with increasing air speeds.
4. The turbulence statistics plots exhibit significant Reynolds dependency under low speed conditions. As no generally valid scaling law could be found, realistic drying experiments on

macroporous materials like porous asphalt need to be performed at full-scale and for the entire range of velocities of interest.

5. Close to the PA surface, the air turbulence profiles are found to be sensitive to surface porosity only at high air speed, mainly due to higher ejections on the porous surface at this speed. This has an important practical implication. At low air speeds (less than 3 m/s), the contribution of surface porosity-induced turbulence to convective drying will be similar for different PAs, provided their porosity profile is similar to that of the specimens used in this study. In such cases, from a macro-scale modelling perspective, this means that a uniform surface porosity can be assumed for PA specimens while performing convective drying simulations on them.

This study took the first steps towards understanding the structure of turbulent airflow near a macroporous material-air interface. For a deeper understanding of drying occurring at such interfaces, further experiments should ensure that appropriate turbulent inflow conditions are achieved to simulate the atmospheric boundary layer (ABL) and that downscaled macroporous models are used.

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Appendix

In this study, the boundary layer height for the moderate and high-speed measurements was located outside the field of view. For the analyses presented in the paper, it was assumed that the velocity observed at the top of the field of view equals the free-stream air speed. This assumption was supported by the fact that the differences between the velocities observed at this point and those recorded by the Pitot tube located inside the wind tunnel in the free stream were small. The sensitivity analysis presented in this appendix aims to verify the impact of that assumption on the values of the boundary layer parameters calculated in Table 2. We define the boundary layer thickness, δ , as the height at which a velocity reaches a fraction h of the free stream air speed U_∞ :

$$\delta = y|_{U=hU_\infty}, \quad (\text{A1})$$

where $h = 0.7, 0.75, 0.8, 0.85, 0.88, 0.9, 0.92, 0.94, 0.96, 0.98$. It is to be noted that $h = 0.99$ in the generally accepted definition of boundary layer thickness. Using this criterion, we re-evaluate the more robust parameters calculated earlier i.e. displacement thickness (Eq. 6), the momentum thickness (Eq. 7) and the shape factor, for each value of h . The results are presented in figs. A1-A3. The sensitivity study focuses on PA8 and PA11.

Figure A1: Sensitivity study of displacement thickness for (a) PA8 and (b) PA11.

Figure A2: Sensitivity study of momentum thickness for (a) PA8 and (b) PA11.

Figure A3: Sensitivity study of shape factor for (a) PA8 and (b) PA11.

In figs. A1-A3, the step-wise increase in the boundary layer parameters at the low speed measurements is due to the spatial resolution of the PIV images. It can be observed that irrespective of the definition of the boundary layer thickness (Eq. A1), the three considered boundary layer parameters are abnormally low at the low air speed, as compared those at the moderate and high air speeds. This is true for both types of PA. The conclusions of our study therefore do not depend on the assumption for

the boundary layer height. On the contrary, the sensitivity study further reinforces the conclusion that there exists a critical air speed, U_{crit} , where $1 < U_{crit} < 2.85$ m/s, below which the flow over PA becomes Reynolds number dependent and below which scaling laws thus lose validity.

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