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Numerical investigation of communicating turbulent boundary layers through porous media

Thomas P. Hunter¹
Faculty of Aerospace Engineering
Delft University of Technology
Kluyverweg 1, 2629 HS, Delft, The Netherlands

Nguyen Anh Khoa Doan
Faculty of Aerospace Engineering
Delft University of Technology
Kluyverweg 1, 2629 HS, Delft, The Netherlands

Francesco Avallone
Department of Mechanical and Aerospace Engineering
Politecnico di Torino
Corso Duca degli Abruzzi 24, 10129 Torino, Italy

Daniele Ragni
Faculty of Aerospace Engineering
Delft University of Technology
Kluyverweg 1, 2629 HS, Delft, The Netherlands

ABSTRACT

The reduction of trailing edge noise can be achieved through the use of porous trailing edges. It has been found that the unsteady interaction between the suction and pressure side of the airfoil is of relevance for noise reduction. Therefore, this study aims at investigating such flow physics. The proposed numerical setup consists of two vertically stacked temporally developing channel flows ($4 \leq (2 + t) \leq 4$, where h and t are the half-channel height and the porous medium thickness respectively). The flow field is solved using the lattice Boltzmann method through PowerFLOW. The two channel flows communicate through a fully resolved porous medium. In this work, the porous medium is a 75% porous Schwarz' P triply periodic minimal surface. Results show span-wise coherent turbulent structures developing on both sides of the porous medium. This is consistent with previous work on turbulent channels over porous media which enable flow in the stream-wise direction. However, the communication between both turbulent boundary layers results in these span-wise structures to be out-of-phase on either side of the permeable material. This phenomenon occurs at a frequency range where the noise reduction of porous trailing edges is the highest when compared to previous studies. A shift in turbulent kinetic energy carrying scales, with more energy being present in larger scales, is also observed. It can be concluded that this would increase the likelihood of interference occurring in the various locations of hydrodynamic pressure fluctuation scattering and as such increase the noise reduction of porous trailing edges.

¹t.p.hunter@tudelft.nl

1. INTRODUCTION

Turbulent Boundary Layer Trailing Edge (TBL-TE) noise is one of the most relevant noise sources for wind turbine blades [1]. The noise generation mechanism centres on the scattering of unsteady hydrodynamic pressure fluctuations in the turbulent boundary layer as these pressure fluctuations are convected past the trailing edge of the blade [2]. Due to the chaotic nature of the hydrodynamic pressure fluctuations in the boundary layer, the resulting acoustic signature is broadband, with its peak being estimated to occur in the range of Strouhal numbers $St = 0.06 - 0.08$ [2], where f is a frequency, δ a boundary layer displacement thickness and U a free-stream velocity.

Several noise mitigation techniques have been proposed in the past decades, as for example the use of trailing edge serrations [3]. Recently, porous trailing edges have also shown great potential for TBL-TE noise reduction, due to their larger noise reduction potential (about 4dB for the serrations [4] and 10dB for the porous trailing edges [5]). However, similarly to serrated trailing edges, the noise reduction potential reduces at lifting conditions [6]. Porous media also result in a high frequency acoustic signature, attributed to the impact of roughness [7]. By enabling a hydrodynamic communication between pressure and suction side of the airfoil, a porous trailing edge provides a milder transition between solid airfoil and the wake [8]. The communication between the two boundary layers was quickly identified as a necessary condition and the largest driver for the noise reduction [8].

The noise reduction mechanism of porous trailing edges has been previously studied both experimentally [9] and numerically [10]. Experiments correlated permeability and noise reduction. However, they also noted the impact of parameters such as tortuosity, which is not independent of permeability. Numerical investigations enabled the reconstruction of the internal hydrodynamic field of the porous medium and identified the ability of porous trailing edges to enable the communication between pressure fluctuations at both sides of the airfoil at lower frequencies. This was observed to lead to a shift in turbulent kinetic energy spectrum to higher frequencies, which are scattered less efficiently. Additionally, other studies highlighted the impact of the non-linearities of the porous trailing edges for the noise reduction [11, 12]. The non-linear permeability parameter has also been associated to the increase in drag in the context of turbulent flows above acoustic liners [13]. This suggests that there is a negative effect on the aerodynamics performance of porous trailing edges which balances the positive one on noise mitigation. The effect of porous walls on drag has been independently studied in past research mostly using the turbulent channel flow (TCF) configuration [14–16] and, in this context, porous walls are related to a lower friction coefficient since they allow for the creation of a slip velocity at the location where the solid wall would be. This comes at the cost of pressure drag which is significant and has been shown to contribute 40 to 400% of drag in acoustic liners [17].

However, the relationship between the pressure release mechanism and aerodynamic performance of porous medium trailing edges remains to be investigated. We propose and use a dedicated numerical setup, based on turbulent channel flows communicating through a fully resolved porous medium. The definition of the porous medium is provided analytically and different flow conditions can be imposed in the channels. The setup focuses on how the flow communication through the flow permeable material modifies the boundary layer on both sides with respect to the smooth non-permeable wall. The modifications of interest include the changes in velocity profiles, turbulent kinetic energy and pressure fluctuations. The first can be related to the aerodynamic performance of a porous trailing edge. The latter two inform on the acoustic performance of such a noise mitigation solution. Here, we use this setup to analyse the instantaneous velocity fields and mean velocity profiles. These enable to characterise the modifications in the velocity fields induced by the communication between the channels and to provide an upper bound for the drag increase of a flat porous plate.

This paper first presents the numerical setup in section 2, focusing on the setup design choices

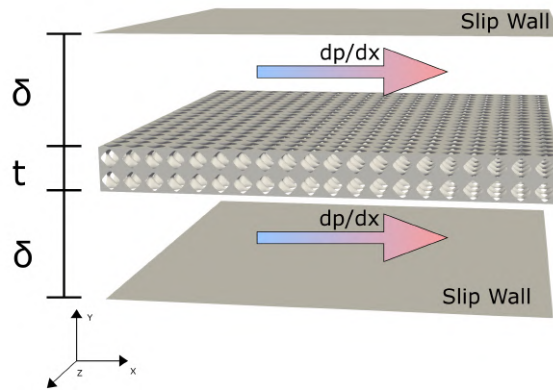


Figure 1: Illustration of the proposed set-up

having been made. This is followed by an analysis of the flow fields as well as their interpretation, in section 3. This analysis is based on instantaneous flow fields, integral values of the turbulent boundary layers and their statistics. Finally, section 4 presents a summary of the main findings of this work and outlines avenues for future investigations.

2. METHODOLOGY

The main considerations for the design of the numerical setup revolved around the need for the setup to be flexible and computationally inexpensive. Both of these requirements would enable the analysis of a wide range of porous media as well as flow conditions. This analysis is necessary to relate integral boundary layer parameters and macroscopic geometrical features of the permeable material. With this understanding, one would be able to optimise the aeroacoustic performance of porous trailing edges.

2.1. Numerical Setup

Our numerical set-up, shown in Figure 1, consists of communicating turbulent channel flows and is composed of two vertically stacked turbulent channels communicating through a porous medium. This set-up allows to study the effect of variations in the porous medium (i.e. scale, porosity, thickness, ...) and flow conditions (stream-wise and wall-normal pressure gradients) on the aerodynamic performance of a porous flat plate. It was inspired by the need to quantify the drag increase associated with acoustic liners in Ref. [17].

To reduce the computational cost of an individual simulation, a channel flow was chosen. Periodic boundary conditions were adopted in the stream- and span-wise directions and slip walls on the top and bottom boundaries of the simulation domain, with the flow being driven by a forcing term analogous to dp/dx . The chosen dimensions of the domain are $4(2 + t) \times 4$, where δ is the half-channel height and t the thickness of the porous medium. While this is a smaller domain size than recommended for domain independence on smooth walls [18], it was shown to be sufficient for studying channel flows over rough walls [13]. In particular, the measure of interest is the difference between non-communicating channel flows and communicating channel flows characteristics. Therefore three different cases are considered: two non-communicating channel flows cases (one with a smooth walled separation, shown in Figure 3a, and one with a blocked porous medium, shown in Figure 3c) and one communicating case (Figure 3b).

The flow in the simulation is driven by a body force term acting in the channels. It can be set independently between the channels to represent different stream-wise and normal pressure gradients. This body force term can be derived from the friction Reynolds number Re_τ as being the opposite of the stream-wise pressure gradient associated with the channel flow. The results shown in this paper

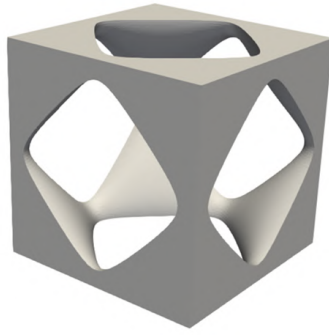


Figure 2: Unit cell of the TPMS P geometry used in this study

correspond to simulations that are carried out at $Re = 590$, in both the channels. The statistics are computed after 10 flow-throughs for a duration of 5 flow-throughs, after being initialised from a low resolution solution.

The chosen porous medium is the triply periodic minimal surface (TPMS) of type Schwarz Primitive 'P'. It is here approximated by its first order decomposition as detailed in Ref. [19]. The porosity is chosen to be $\phi = 0.75$ and scaled such that the unit cell of the porous medium is 2 mm . A typical unit cell of such a geometry is shown in Figure 2. The thickness is kept fixed in this study at $t = 4\text{ mm}$ and the half-channel height is taken to be 10 mm . Moreover, the use of TPMS further enables a great degree of flexibility with the ability to generate a wide range of porous media that are defined analytically [20]. The dimensions were chosen to obtain a porous medium that is comparable to previous studies, namely [21] which was performed numerically and [22] which was done experimentally. The ratio of pore diameter to boundary layer height is approximately $d_p = 17\%$. While the half-channel height is similar to the boundary layer height of Ref. [23], the thickness corresponds to the approximate thickness of a NACA 0018 of chord length 0.2 m in the last 5% of the chord, where the noise reduction was observed to be more considerable [24]. The blocked porous medium is obtained by adding a solid plate in the centre of the simulation domain of thickness $t_b = 0.02 L_{ref}$, thereby preventing the communication between the two channels.

The advantage of the proposed Communicating Turbulent Channel Flow (CTCF) configuration in the study of the impact of communication in porous trailing edges is the ability to independently vary many parameters. For instance, characteristics associated with the porous medium can be independently varied, such as the porosity, the unit cell size L_{ref} and thickness t . The flow variables considered are the boundary layer thickness (here the half-channel height), the stream-wise pressure gradient dp/dx and the pressure differential across the porous medium. The ability to independently vary these variables should enable discerning either or $t =$ as effective design criteria in the future for instance.

In addition, by lightly modifying the proposed set-up to a spatially developing CTCF where a total pressure inlet and static pressure outlet can now be used, the velocity in the channels can also be individually controlled and the impact of the porous trailing edge length can be quantified. It was estimated that an adaptation length of $25t$ after a zigzag trip is used to trigger transition is necessary to obtain a fully developed turbulent channel flow, greatly increasing the computational cost of such a simulation, which is why it is not considered in this initial work.

The geometry is discretised using a resolution of 32 voxels. This resolution is required for two reasons. On the one hand, in the smooth-wall case, the obtained wall coordinate of the first voxel is y^+ of 2.4. Any lower resolution would lead to issues with the wall model as the first voxel would be in the buffer region of the boundary layer. On the other hand, the geometry of the porous medium requires this resolution to ensure sufficient geometrical fidelity. The wall coordinate of the first voxel is then $y^+ < 2$. This is consistent with the best practices of PowerFLOW [10], being a wall-modelled VLES solver.

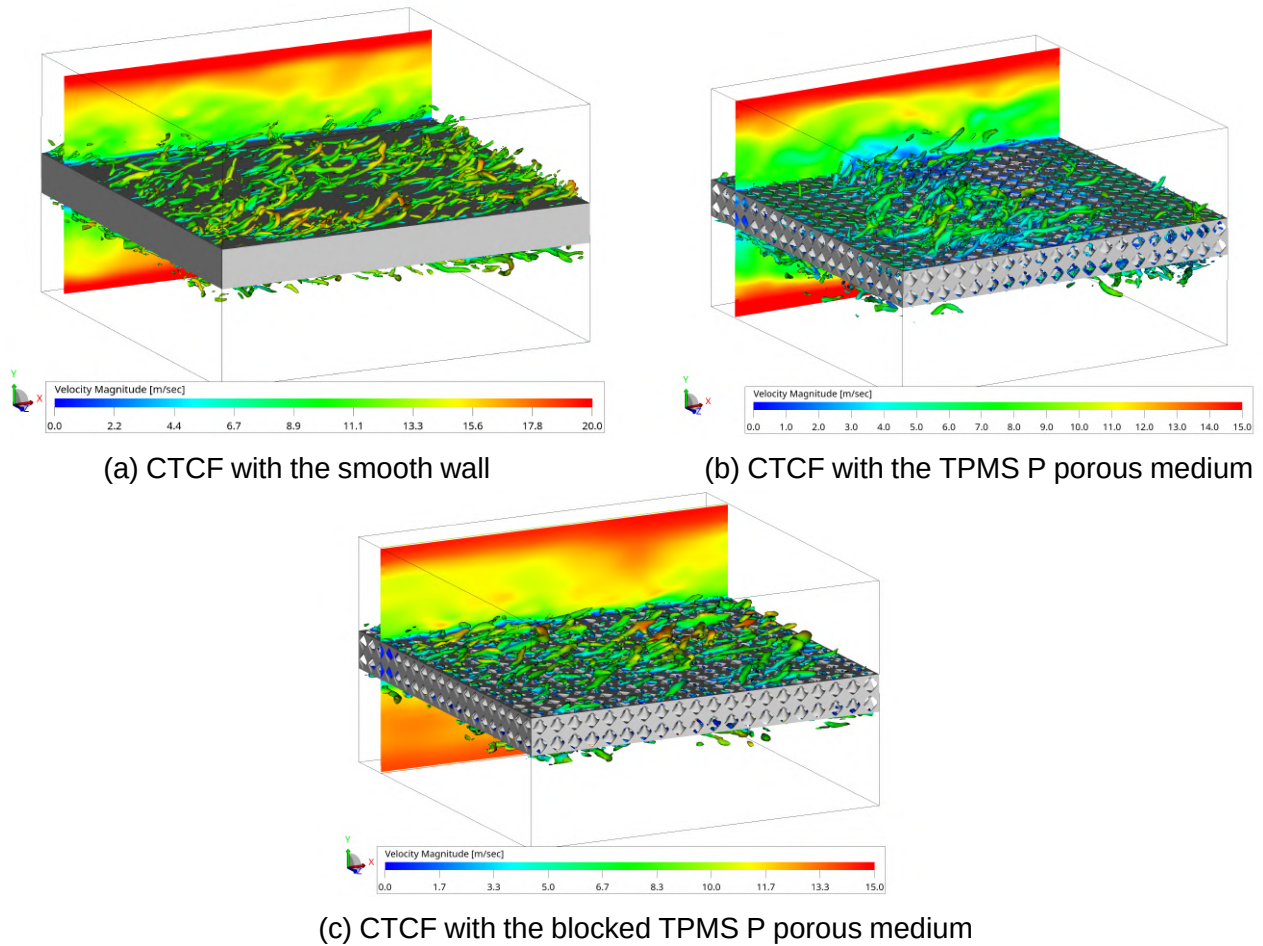


Figure 3: Instantaneous iso-surfaces $\omega = 2 \times 10^7 \text{ s}^{-2}$, coloured with velocity magnitude, also shown in the cut plane $z = 0.5$.

The most expensive simulation, the blocked porous medium, was then composed of $10^4 \times 10^4$ for a total cost of 24×10^3 CPU hours using 120 CPUs on an Intel(R) Xeon(R) CPU E5-2660v3 based platform.

3. RESULTS

3.1. Instantaneous Flow Field

Figure 3 shows three typical instantaneous flow fields for $Re = 590$. The ω_2 vortex criterion, shown in the figure, is used to identify vortical structures in the solutions [25].

From this figure, it is possible to qualitatively assess that the presence of a porous medium, as shown in Figure 3b, results in the apparition of span-wise coherent structures, consistent with reports regarding TCF over permeable surfaces [15, 26, 27]. The integral lengths of these structures was computed taking the correlation length of the wall-normal velocity in both the stream- and span-wise

Table 1: Correlation lengths in stream- and span-wise direction at 10% ($y^+ = 73$)

Case	x^+	z^+
Solid	20×10^1	$7:0 \times 10^2$
Blocked	21×10^1	$8:1 \times 10^2$
Porous	31×10^1	$1:7 \times 10^1$

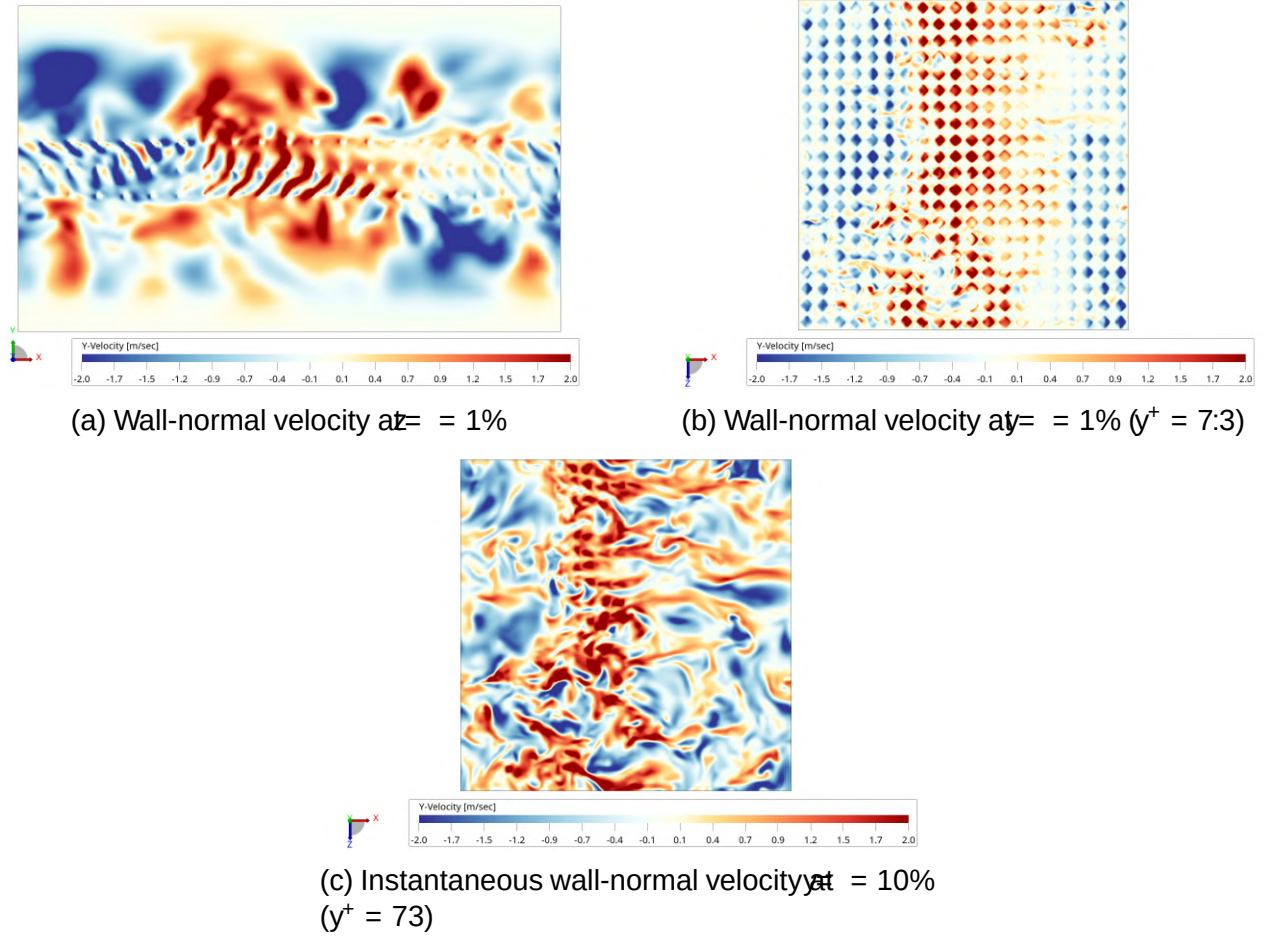


Figure 4: Instantaneous flow visualisations of the wall-normal velocity

directions [10]. The obtained correlation lengths are given in Table 1. It is possible to see that the smooth and blocked-porous cases have similar correlation lengths while the communication leads to an increase in both stream- and span-wise correlation lengths (and z respectively). The increase in stream-wise correlation length can be explained by observing that the vortical structures shown in Figure 3b are convected vertically, as shown in Figure 4a. The vortical structures thus reach higher velocity regions in the boundary layer and are stretched. More significantly, the doubling of the correlation length in the span-wise direction indicates that the flow is strongly span-wise coherent. This is a much larger increase than the sole presence of the porous medium in the blocked case.

Nonetheless, the main impact of communication between the channels is the coherence on either side of the porous medium. This is a consequence of the hydrodynamic pressure fluctuations becoming coherent and out-of-phase between the channels. This strengthens the normal motion of the span-wise coherent structures since low pressure regions are associated to high pressure regions in the other channel. These can lead to a net normal pressure differential to drive flow through the porous medium, contrary to previous observations on implementation of porous trailing edges [21]. This is shown in Figure 4. This figure shows both stream-wise (Figure 4a) and span-wise distributions (Figure 4b and Figure 4c) of the wall-normal velocity. Figure 4c illustrates the lasting effect of the communication in the boundary layer. The existence of flow through the porous medium would point to the existence of a regime similar to the fully rough regime described in turbulent flows over acoustic liners [17].

Previous studies of noise reduction using porous trailing edges did not document flow through the porous medium [23]. This warrants further investigation using a spatially resolved CTCF in order

Figure 5: Cross-correlation map of the pressure with respect to the point (0.02,0.003,0.02), in the x-y plane, band-filtered in the frequency range $f = 50 - 1000$ Hz

Figure 6: Cross-correlation map of the pressure with respect to the point (0.02,0.003,0.02), in the z-y plane, band-filtered in the frequency range $f = 50 - 1000$ Hz

to determine the distance required for the build up of these span-wise coherent vortical structures. However, the communication allowing for the build up of coherence between the grazing flows can be hypothesised to be the source of the shift in the energy spectrum of the field as reported in [10].

Figure 4 also leads to the observation that the flow through is limited in extent to the lower half of the boundary layer. It is possible that the wake effects limit the extent of this wall-normal velocity. The wake effects are shown to occur around $y/d = 400$ in Figure 7.

We observed that the span-wise coherent structures were stable and convected in time. This justified the use of a cross-correlation map, as shown in Figure 5 and Figure 6. This band-filtered cross-correlation map shows the strong wall-normal anti-correlation of the pressure on either side of the porous medium. Moreover, the chosen band indicates that this mechanism mainly occurs between frequencies of 50 and 1000 Hz. The frequency range can be made adimensional taking the chord Strouhal number $St_c = f c / U_1$, where $c = 0.2$ m and $U_1 = 20$ m/s as in [21]. This leads to a range of $St_c = 0.5 - 10$ that corresponds to the range of frequencies where porous trailing edges reduce noise most effectively. One can also observe the large span-wise correlated region in Figure 6.

3.2. Boundary Layer Characteristics

The modification of the boundary layers induced by the flow communication is further analysed and quantified in Figure 7, where the intrinsic average stream-wise velocity profiles are shown. First, the main observation that can be made for the addition of the porous medium in the simulation is that the mean velocity is approximately halved compared to the smooth wall case. While the force acting on the porous medium in the stream-wise direction is equal for all the cases presented here (due to the nature of the set-up with constant forcing), the addition of the porous medium results in a vast increase in drag. The mean velocity in the channels is therefore lower, leading to lower skin friction. However, the presence of the porous medium induces additional pressure drag. This is mostly seen in the intrinsic mean velocity profiles, shown in Figure 7.

The mean profiles are obtained by averaging in both time (over 5 flow throughs) and in space (over the periodic directions). In this figure, one can observe the consequential wake at the centre of the channels. This is a direct result of the additional drag which greatly reduces the mean velocity in the channels and that the simulation domain is bounded by slip walls in the wall-normal direction.

This velocity deficit in the boundary layer is computed in terms of u^+ , which is the velocity difference between the smooth wall and porous wall simulation in the log-layers (approximately corresponding to the blue line in Figure 7). The line indicates the log-law that the cases follow