

A NEW SURFACE BOUNDARY CONDITION FOR LES OVER A ROUGH-TO-SMOOTH TRANSITION

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1. INTRODUCTION

Understanding the effects of surface roughness transitions on the spatial distribution of surface shear stress and velocity is key to improving predictions of turbulent transport in the atmospheric boundary layer (ABL). For example, most atmospheric numerical models require as lower boundary condition the specification of the surface shear stress as a function of the grid-averaged velocity field. In large-scale models, such as weather and climate models, the surface boundary condition needs to account for the effects of sub-grid surface heterogeneity on the spatial distribution of the surface shear stress and its relation with the velocity in the surface layer (Wieringa *et al*, 1986; Taylor *et al*, 1987; Mason *et al*, 1988; Claussen *et al*, 1990; Zeid *et al*, 2004). In the case of higher resolution numerical models, such as large-eddy simulations (LESs), where much of the surface heterogeneity is explicitly resolved, the surface boundary condition still requires the calculation of local (spatially filtered) surface shear stress as a function of the filtered fluctuating velocity at the lowest computational grid points. Currently, these models rely on the application of Monin-Obukhov similarity theory (the log law under neutral conditions) using local values of the filtered velocity. However, the accuracy of this approach is questionable since similarity theory is strictly valid only when applied over homogeneous surfaces and considering averaged quantities. Improvement of these boundary condition parameterizations in simulations of ABL flow over heterogeneous surfaces requires a better understanding of the effects of surface roughness transitions on the relation between surface shear stress and velocity fields.

Several models with different levels of complexity have been proposed to estimate the spatial distribution of surface shear stress and velocity after a roughness transition (e.g. Elliott *et al*, 1958; Mulhearn *et al*, 1978; Panofsky *et al*, 1964; Townsend *et al*, 1965; Townsend *et al*, 1966). The simplest and most common analytical models, introduced by Elliott (1958) and Panofsky *et al* (1964), were obtained assuming a constant and a linear vertical distribution (respectively) of the friction velocity within the internal boundary layer (IBL). Rao *et al* (1973) used a numerical approach based on the Reynolds-averaged Navier-Stokes equations with a second-order closure model that includes a set of differential transport equations for the components of the Reynolds stress tensor. Rao's simulated velocity and surface shear stress profiles showed good agreement with the experimental field measurements of Bradley (1968). Recently, Zeid *et al* (2005) used a small computational domain to perform a very high resolution large-eddy simulation of the

same roughness transitions using Lagrangian dynamic subgrid-scale models and showed that the simulated surface shear stress fields agreed reasonably well with the experimental field data of Bradley (1968).

A common simple approach used to relate surface shear stress and velocity in the surface layer is Elliott's model (Elliott *et al*, 1958), which assumes that the downwind velocity profile is in equilibrium with the new surface and, therefore, follows a logarithmic profile all the way up to the internal boundary layer height δ_i :

$$U = \frac{u_{*2}}{k} \ln \left(\frac{z}{z_{02}} \right), \quad (1)$$

where U is the average velocity at elevation z , u_{*2} is the friction velocity, z_{02} is the downwind surface roughness, and k is the von Kármán constant. This equation can be derived by assuming a constant shear stress along the vertical for $z < \delta_i$ and an equilibrium value of unity for the nondimensional wind shear $\Phi_m = (kz/u_{*2})(\partial U/\partial z)$. For time-averaged surface shear stress (τ_s) predictions, Equation (1) can be written as

$$\tau_s = \left[\frac{kU}{\ln(z/z_{02})} \right]^2. \quad (2)$$

It is important to note that, due to constant vertical turbulent shear stress assumption, this model produces an unrealistically sharp stress discontinuity at the top of the internal boundary layer $z = \delta_i$. For the internal boundary layer (IBL) depth δ_i , Elliott proposed the following relation:

$$\eta = (0.75 - 0.03M') \xi^{0.8}, \quad (3)$$

where η , M' and ξ are non-dimensional parameters defined as $\eta = \delta_i/z_{02}$, $M' = \ln(z_{02}/z_{01})$ and $\xi = x/z_{02}$. z_{01} and z_{02} are the upwind and downwind aerodynamic surface roughness, respectively, and x is the distance measured from the roughness change.

To avoid an abrupt change in the surface shear stress at the internal boundary layer height δ_i , Panofsky *et al* (1964) considered a linear variation of the friction velocity with respect to height within the IBL:

$$u_* = u_{*1} \left[(1 - S) + S \frac{z}{\delta_i} \right], \quad (4)$$

where $S = (u_{*1} - u_{*2})/u_{*1}$ is a non-dimensional measure of the relative change in surface stress associated with the transition. u_{*1} and u_{*2} are the upwind and downwind friction velocity respectively.

As in Elliott's model, the velocity and surface shear stress distributions are derived by assuming a value of unity for the nondimensional wind shear. This yields

$$U = \frac{u_{*1}}{k} \left[(1 - S) \ln \left(\frac{z}{\delta_i} \right) + S \frac{z}{\delta_i} \right] \Leftrightarrow \quad (5)$$

$$U = \frac{u_{*2}}{k} \ln \left(\frac{z}{z_{02}} \right) + \frac{u_{*1} - u_{*2}}{k} \left(\frac{z}{\delta_i} \right)$$

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which implies

$$\frac{\tau_{s2}}{\tau_{s1}} = \left[1 - \frac{kU/u_{*1} - \ln(z/z_{02})}{z/\delta_i - \ln(z/z_{02})} \right]^2 \quad (6)$$

τ_{s1} and τ_{s2} are the upwind and downwind surface shear stress, respectively. Note that Panofsky and Townsend's model (hereon referred also as P-T) requires an explicit estimation for the internal boundary layer height δ_i . Panofsky and Townsend proposed an IBL depth-fetch relationship given by

$$4k^2(\xi - \xi_0)/\eta = \ln\eta - 5 + \frac{1}{2}M + \frac{4 - \frac{7}{6}M - \frac{1}{4}M^2}{\ln\eta - 1 + \frac{1}{4}M} + \frac{4 + \frac{7}{6}M + \frac{1}{24}M^2 + \frac{1}{16}M^3}{(\ln\eta - 1 + \frac{1}{4}M)^2}, \quad (7)$$

where $M = \ln(z_{01}/z_{02})$ and $\xi_0 = 0$ for $M = 1.65$ (smooth-to-rough transition) and $M = 2.17$ (rough-to-smooth transition). A recent review on this and other IBL height models can be found in Savelyev *et al* (2005).

Experience suggests that the predictions from both Elliott and P-T models can differ substantially from observations. This can be explained considering that, as shown by Rao *et al* (1973), the non-dimensional wind shear, dissipation length scale, mixing length scale, and ratio of stress to turbulent kinetic energy downwind of a roughness transition are found to differ significantly from their equilibrium values.

In this paper, a simple new analytical model is proposed to predict the spatial distribution of wind velocity and surface shear stress downwind of a rough-to-smooth surface transition. First, a wind tunnel experiment is presented in Section 2. The experiment was designed to study the performance of different simple analytical models. In section 3, the models of Elliott and Panofsky-Townsend are tested. The proposed alternative new simple model is presented in Section 4, and its performance and its performance is evaluated in Section 5 using our wind tunnel data as well as Bradley's field data. Finally, a summary is given in Section 6.

2. EXPERIMENTAL SETUP

A rough-to-smooth surface transition has been designed and set up in the boundary layer wind tunnel of the Saint Anthony Falls Laboratory at the University of Minnesota with the goal of studying the performance of different models for the spatial distribution of wind velocity and surface shear stress downwind of the transition. The boundary layer wind tunnel has a plan length of 37.5 m with a main test section fetch of roughly 15 m. There is a contraction with a 6.6:1 area ratio upwind of the test section along with flow conditioning/turbulence control consisting of a coarse wire mesh and honeycomb flow-straightened. The tunnel is driven by a 200 hp fan and is operated as a closed return loop. The turbulence intensity, in the center of the wind tunnel, is approximately 0.25% for a 10 ms⁻¹ freestream velocity. More details on the wind tunnel can be found in Carper *et al* (2008).

Wind tunnel velocity was measured using Pitot static tubes (mainly for calibration) and constant temperature

anemometry (CTA). Two types of CTA were considered: single-normal (SN) and crosswire (XW or x-wires) probes. The probes are made with 5.0 μm tungsten wire and are connected to an A.A. Lab Systems AN-1003 10-channel CTA system. During the calibration and measurements the temperature fluctuations were kept within a $\pm 0.5^\circ\text{C}$ range to avoid bias errors due to thermal drift of the voltage signal. For more details on the calibration see Bruun (1995).

The rough-to-smooth transition was created by placing 7 m length of wire mesh on the wind tunnel floor upstream of an aerodynamically smooth flat plate. The woven-wire mesh is considered a k-type roughness (see Jimenez, 2004) and has an average height $k_0=3$ mm with an aerodynamic roughness length $z_{01}=0.5$ mm.

A turbulent boundary layer is developed upstream with the help of a tripping mechanism (8 cm picket fence) located at the exit of the wind tunnel contraction where the test section begins. The turbulent boundary layer is allowed to grow in zero pressure gradient conditions by adjustment of the wind tunnel ceiling. The upstream roughness induces a strong change in the momentum flux near the surface, maintaining a well-developed surface layer with constant shear stress and a logarithmic velocity profile. The experiments were conducted with a 10 ms⁻¹ freestream flow velocity and a turbulent boundary layer depth of $\delta = 40$ cm at the roughness transition location.

A SN hotwire (boundary layer type) and x-wire anemometer were used to measure surface shear stress and wind velocity (respectively) at different positions downstream of the transition ($x/\delta=0.1, 0.15, 0.2, 0.25, 0.375, 0.5, 0.75, 1.0$ and 1.5) and various heights (for the x-wire) within the internal boundary layer. The single hotwire was placed in the viscous sublayer, directly over the smooth surface to measure the surface shear stress. A schematic and picture of the experimental setup are shown in Figure 1. Experimental studies by Chew *et al* (1998), Khoo *et al* (1998), and Alfredsson *et al* (1988) have shown that accurate instantaneous surface shear stress measurements can be obtained using a slightly elevated hotwire. During data collection the two sensors voltage signatures were sampled simultaneously at a rate of 20 kHz for measurement period of 60 s.

A review of research on rough-wall boundary layers by Jimenez (2004) and an experimental study by Castro *et al* (2006) suggest that boundary layers behave differently depending on ratio of boundary layer height (δ/k_0) with a change in behavior when $\delta/k_0 > 80$, which is typical for ABL. Previous wind tunnel experiments (Antonia *et al*, 1972; Mulhearn (1978); Cheng *et al*, 2002; Castro *et al*, 2006) have provided valuable results but have δ/k_0 on the order of 20. These relatively low ratios of boundary layer height to roughness element height are not typical for land surface transitions because the effect of their roughness elements reaches further into the wind tunnel boundary layer than the effect of rough terrain does in the ABL. Thus, the roughness chosen in those wind tunnel studies may not provide a large enough range of length scales to allow a true equilibrium surface layer to develop. The setup used in this study maintains a $\delta/k_0 = 133$ to ensure that inner and outer scales of the boundary layer, and hence its structure, are well developed.

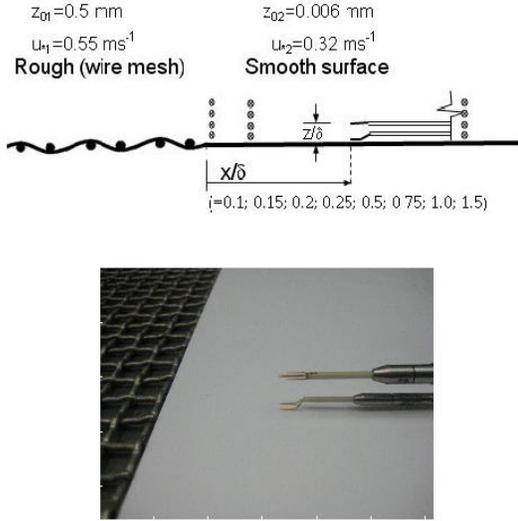


FIG. 1: Schematic of the rough-to-smooth transition and measurement locations (top) and picture of the single hotwire and x-wire probes placed downwind of the surface transition (bottom).

The zero pressure gradient boundary layer, developed upstream of the transition, had a Reynolds number based on the surface shear stress of $Re_\tau \approx 1.5 \times 10^4$, a boundary layer thickness of $\delta = 40$ cm, a friction velocity of $u_{*1} = 0.55$ ms⁻¹ and a freestream velocity $U_1 = 10$ ms⁻¹. In this condition, the upwind transition boundary layer is in the fully rough regime (Jimenez, 2004). The smooth surface consists of the finished wooden floor of the tunnel with a window of flat plate that lies flush and sealed with the floor. The floor surface has been verified to be aerodynamically smooth using measurements of mean velocity before the wire mesh was installed upwind. A boundary layer forming over only the smooth floor has approximately the same height as the boundary layer over the rough surface but with a friction velocity $u_{*2} = 0.32$ ms⁻¹.

Calibrations of the single and x-wire anemometers were performed at the beginning of the experiment run. The x-wire was calibrated in the freestream region against a Pitot-static probe, at seven angles for each of seven velocities. A cubic-spline table calibration method was then used to determine the two instantaneous velocity components from the two instantaneous voltage signatures. The single hotwire used as a surface shear stress sensor was calibrated against a Preston tube (see Patel, 1965) connected to the same pressure transducer considering ten different free stream velocities. The single hotwire and Preston tube were placed over a smooth flat plate in the freestream region to avoid any disturbance.

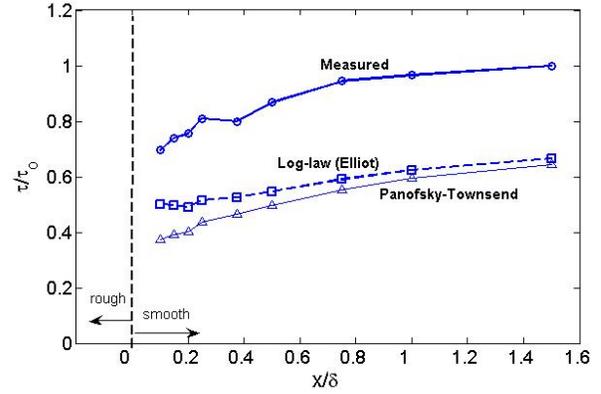


FIG. 2: Comparison between measured average surface shear stress and the predictions from the models of Elliot (equation 2) and Panofsky-Townsend (equation 6). Downwind distance is normalized with the boundary layer height $\delta = 40$ cm. Surface shear stress is normalized with its downwind equilibrium value (τ_0)

3. ANALYSIS OF ELLIOTT AND PANOFSKY-TOWNSEND MODELS FOR SURFACE SHEAR STRESS

The average surface shear stress measured with the single hotwire, normalized with the equilibrium downwind surface shear stress (τ_0), is plotted in Figure 2 as a function of the normalized distance downwind from the transition. As expected, the shear stress increases with distance from the transition and asymptotes the equilibrium shear stress on the smooth surface. At a distance slightly larger than the boundary layer depth, the shear stress is close to its equilibrium value. The surface shear stress predicted with the Elliott and P-T models, using the velocity measured at a height of $z = 1.35$ cm in Equations (2) and (6), respectively, are also plotted in Figure 2 for comparison. Both models clearly underestimate the value of the surface shear stress at each of the downwind locations under consideration.

It is important to notice that P-T's surface shear prediction should always be smaller than Elliott's prediction when they are based on the velocity at the same height. This is due to the fact that the P-T model (Equation 5) adds a positive term to Elliott's velocity formula, which necessarily implies a lower surface shear stress.

Ideally, the surface shear stress prediction, obtained with any given model should have no (or small) dependence on the height at which the velocity is measured. Figure 3 shows Elliott's surface shear stress prediction at different downwind positions using velocities measured at different heights. From this figure it is clear that Elliott's surface shear stress prediction is strongly dependent on the height where the model is applied. It is interesting to note that the prediction improves as the considered height approaches the IBL height. P-T's surface shear stress predictions were also found to have a similar strong dependence (not shown here) on the height at which the model is applied.

A particular case of Elliott's approach is given by

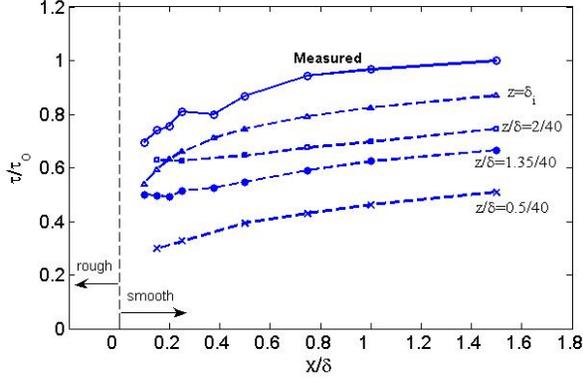


FIG. 3: Measured and modelled surface shear stress obtained with Elliott's log-law model (equation 2) using velocity measurements at different heights z . Downwind distance and height are normalized using the boundary layer height $\delta=40$ cm. Surface shear stress is normalized with its downwind equilibrium value (τ_0)

Jensen (1978), who proposed an expression for the ratio between downwind and upwind shear stresses (τ_{s2}/τ_{s1}) based on applying Elliott's equation at $z = \delta_i$:

$$\frac{\tau_{s2}}{\tau_{s1}} = \left[1 - \frac{M}{\ln(\delta_i/z_{02})} \right]^2. \quad (8)$$

As shown in Figure 3, this formula yields the right trend in the surface shear stress, but (in this case) it underestimates its magnitude by about 15% at all positions downwind of the transitions. It is important to note that, in order to use this model, an estimate for the internal boundary layer height is required. In Figure 3, for the case of $z = \delta_i$ (Jensen's model), the IBL growth equation proposed by Elliott (Equation 3) has been used. Note that unlike Elliott and P-T parameterizations, Jensen's model cannot predict the velocity distribution throughout the IBL.

Previous studies (e.g. Bradley, 1968) suggest that vertical velocity profiles downwind of a roughness transition have a log-nonlinear behavior, which differs from the log-linear models of Elliot and P-T. Next we propose a simple model that tries to reproduce the log-nonlinear velocity distribution pattern observed within the internal boundary layer.

4. ALTERNATIVE SIMPLE MODEL FOR VELOCITY AND SURFACE SHEAR STRESS PREDICTIONS

As pointed out by Garratt (1990), the observed behavior of velocity profiles within internal boundary layers suggests that they might be described through a modified logarithmic law of the general form

$$U = \frac{u_{*2}}{k} \ln \left(\frac{z}{z_{02}} \right) + f(z/\delta_i), \quad (9)$$

where the function $f(z/\delta_i)$ should have the following limiting values

$$f = \begin{cases} \frac{u_{*1}}{k} \ln \left(\frac{z}{z_{01}} \right) - \frac{u_{*2}}{k} \ln \left(\frac{z}{z_{02}} \right), & z/\delta_i \geq 1 \\ 0, & z/\delta_i < 1. \end{cases} \quad (10)$$

The limiting values for $f(z/\delta_i)$ reflect the effect of boundary conditions given by the upstream logarithmic velocity profile at z/δ_i and the equilibrium logarithmic velocity profile close to the downwind surface.

One possible simple formulation for the function $f(z/\delta_i)$, that satisfies the conditions given by Equation (10), can be obtained by weighting the function $f(z/\delta_i)$ by a nondimensional parameter λ such that $0 < \lambda < 1$ for $z/\delta_i < 1$. This yields the following equation for the velocity distribution within the IBL:

$$U \approx \frac{u_{*2}}{k} \ln \left(\frac{z}{z_{02}} \right) + \lambda \left(\frac{u_{*1}}{k} \ln \left(\frac{z}{z_{01}} \right) - \frac{u_{*2}}{k} \ln \left(\frac{z}{z_{02}} \right) \right), \quad (11)$$

which can also be written as

$$U \approx (1 - \lambda) \frac{u_{*2}}{k} \ln \left(\frac{z}{z_{02}} \right) + \lambda \frac{u_{*1}}{k} \ln \left(\frac{z}{z_{01}} \right). \quad (12)$$

Note that Equation (12) implies that $u(z)$ is estimated as a combination of two limiting log laws, one corresponding to the upwind velocity profile and the second corresponding to the so-called equilibrium sublayer, where the flow is in equilibrium with the downwind surface. In order to satisfy the conditions given in Equation (10), the weighting parameter λ should increase monotonically as z/δ_i increases. Our wind tunnel measurements (Figure 4) and also previous studies (e.g., Bradley, 1968) suggest that λ does not follow strictly a linear relation in terms of z/δ_i . In order to obtain a simple expression for the non-dimensional parameter λ , it is important to identify the variables that have a dominant effect in the shape of the velocity profile. In addition to z and δ_i , previous studies (e.g. Wood, 1982) have shown that the largest of the two aerodynamic roughnesses, z_{01} , is the more relevant parameter of the two. Taking this into consideration, a simple non-linear monotonically increasing function that satisfies the limiting conditions in Equation (10) and induces a non-linear log velocity profile behavior is

$$\lambda = \ln(z/z_{01})/\ln(\delta_i/z_{01}). \quad (13)$$

5. EVALUATION OF THE NEW MODEL

Figure 4 shows a comparison between mean velocity profiles measured downwind of the rough-to-smooth transition and the corresponding profiles estimated using the simple new formulation given by Equations (12) and (13). Our results show an excellent agreement between modeled and measured velocities. It is important to observe that the velocity profiles do not follow a logarithmic law within the IBL. In fact, velocity profiles show a clear curvature (log-nonlinear behavior) which cannot be reproduced by Elliott's log-law model.

Next, we evaluate the performance of the model to predict the local value of the surface shear stress as a function of the velocity at different locations in the IBL. Figure 5 shows a comparison between the surface shear stress measured at different positions downwind of the surface transition and the estimated surface shear stress

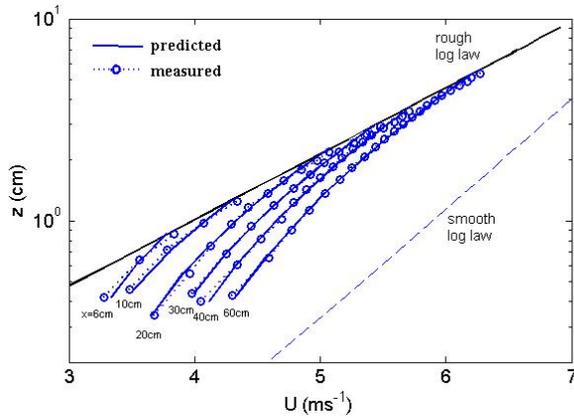


FIG. 4: Adjustment of wind velocity profiles behind rough-to-smooth transition ($z_{01}=0.05$ cm, $z_{02}=0.00064$ cm) measured in the wind tunnel (continuous lines correspond to predictions from the new model).

obtained using the new formulation with the velocity measured at $z = 0.5$ and 1.35 cm. For comparison, results from the Elliott's model is also included. The new model markedly improves the surface shear stress prediction. Moreover, the prediction of the new model shows very small dependence on the height in the IBL at which the model is applied. Despite the remarkable performance of the model to capture the evolution of the surface shear stress near the transition, the model is found to overestimate the value of the equilibrium value of the surface shear stress away of the transition by nearly 15%.

In order to gain further insight on the performance of the new model, in Figure 6 the value of the parameter λ obtained with the new model (Equation 12) is compared with the 'exact' value calculated from the measured velocity. The value of λ is presented as a function of distance from the transition (x/δ_i) and for three different heights ($z=\text{constant}=1.35$ cm, $z/\delta_i = 0.5$, and $z/\delta_i = 0.75$, respectively). Note that for a given height (e.g., $z=1.35$ cm), the value of λ decreases with downwind distance (Figure 6a). This is consistent with the fact that, at that height, the wind velocity becomes more adjusted to the downwind surface and, consequently, the model should have a larger relative contribution from the downwind log law (smaller λ in Eq. 12). In Figure 6(b)-(c) the value of λ is nearly constant due to the fact that the height relative to the boundary layer (z/δ_i) remains constant. In all cases, the new model is able to capture the spatial distribution of λ , which is key for the good performance of the model shown in Figures 4 and 5.

In order to further test the performance of the new formulation, we have also used the field data of Bradley (1968). In that experimental study, surface shear stress distribution and wind velocity profiles were carefully characterized downwind of a spikes-to-tarmac transition. The surface roughnesses estimated by Bradley (1968) were $z_{01}=0.25$ cm for the spikes and $z_{02}=0.002$ cm for the tarmac. In a later study, Nemoto (1971) showed that the values of z_{01} , estimated from Bradley's velocity profiles, range from 0.14 cm to 0.008 cm and those of z_{02} range

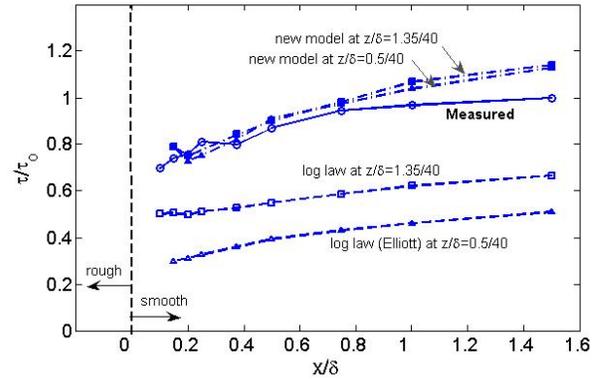


FIG. 5: Measured and modelled surface shear stress obtained with Elliott's log-law model (Equation 2) and the proposed new model using velocity measurements at two different heights. Downwind distance and height are normalized using the boundary layer height $\delta=40$ cm. Surface shear stress is normalized with its downwind equilibrium value (τ_0)

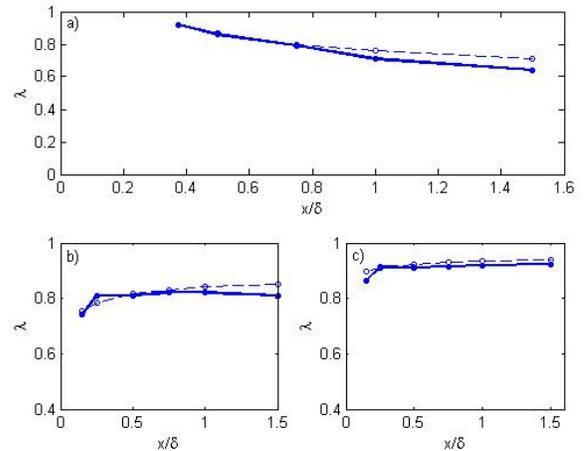


FIG. 6: Spatial distribution of the weighting factor λ as a function of downwind distance for three different vertical positions: (a) $z=1.35$ cm; (b) $z/\delta_i = 0.5$; and (c) $z/\delta_i = 0.75$. Dashed lines correspond to the model weighting factor as given by equation (13). The solid lines correspond to the 'exact' factor obtained from the measurements.

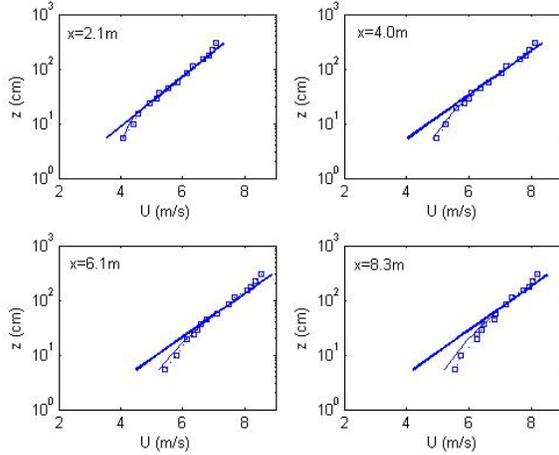


FIG. 7: Wind velocity profiles behind rough-to-smooth transition. Dotted lines and opens symbols correspond to the measurements of Bradley (1968), while the solid lines are the predictions given by the new model.

from 0.0015 cm to 0.00023 cm. This was later corroborated by Rao *et al* (1973) who reported that values of z_{02} in the range 0.0002 to 0.005 cm are equally plausible. He attributed this wide scatter for the smooth surface due to the difficulty associated with extrapolating the neutral equilibrium wind profile data. In this comparison, we follow the same procedure considered by Nemoto (1972), i.e., we analyze each profile and adjust z_{01} to the velocity profile. The roughness z_{02} is estimated from the farthest velocity profile, which is better adjusted to the downwind roughness.

Figure 7 shows the comparison between the wind velocity profiles measured by Bradley at different positions ($x=2.1, 4.0, 6.1$ and 8.3 m) downwind of the transition and the velocity profiles predicted with the new model. The modeled velocity profiles show overall good agreement with the measurements. In figure 8, the prediction of the surface shear stress obtained with the new model is compared with the measurements of Bradley for different positions downwind of the surface transition.

The modeled shear stress falls within the range of the measurements except for the further distance, where, like in the case of the wind tunnel comparison, the model appears to slightly overestimate the value of the surface shear stress. These results contrast with Elliot's and P-T's predictions (also presented by Bradley and included in Figure 8) that systematically underestimate the surface shear stress at all positions.

6. SUMMARY

A simple new model is proposed to describe the distribution of wind velocity and surface shear stress downwind of a rough-to-smooth surface transition. The wind velocity is calculated as a weighted average between two limiting logarithmic profiles: the first log law, which is recovered above the internal boundary layer height, corresponds to the upwind velocity profile; the other log law is adjusted to the downwind aerodynamic roughness and local surface

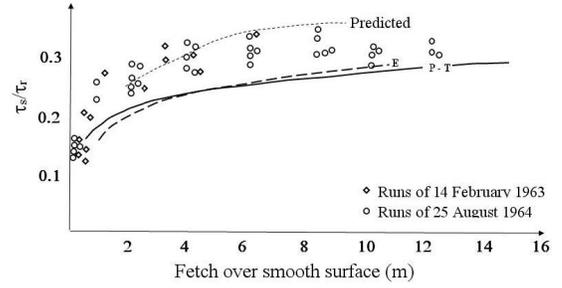


FIG. 8: Surface shear stress distribution measured in the field experiment of Bradley (1968) (symbols) and corresponding predictions obtained with the new model as well as Elliott's and P-T's models. (τ_s and τ_r are the smooth and rough surface shear stress respectively).

shear stress, and it is recovered near the surface, in the equilibrium sublayer. The proposed non-linear form of the weighting factor is equal to $\ln(z/z_{01})/\ln(\delta_i/z_{01})$, where z , δ_i and z_{01} are the elevation of the prediction location, the internal boundary layer height at that downwind distance, and the upwind surface roughness, respectively. Unlike other simple analytical models, the new model does not require the assumption of a constant or linear distribution for the turbulent shear stress within the internal boundary layer. By setting the weighting factor to zero, Elliott's model is recovered.

The performance of the new model is tested with our wind tunnel measurements and also with the field data of Bradley (1968). The ability of the new model to reproduce both the surface shear stress and the velocity distributions is compared with other existing analytical models, namely Elliott's and P-T's models. These two models are found to underestimate the surface shear stress calculated using the wind velocity measured at different heights within the IBL. In addition, prediction of the surface shear stress obtained with both models shows a strong dependence on height. When the height approaches the internal boundary layer depth δ_i , Elliott's prediction improves. This particular case corresponds to the model of Jensen (1978). However, Elliott's model consistently underestimates the surface shear stress when applied using the velocity at lower locations within the internal boundary layer. This underestimation is even more pronounced for the P-T model due to the fact that, by construction (Eq. 5), P-T's model always predicts a smaller surface shear stress than Elliot's model for any given height and corresponding velocity. The proposed new model yields surface shear stress distributions that are more realistic and, at the same time, have much smaller dependence on height, compared with the predictions from the models of Elliot and P-T. These results highlights the potential of the new model to be used in improved parameterizations for the surface shear stress in large-eddy simulations of turbulent boundary layer flows over heterogeneous surfaces. The new model is also found to capture the measured downwind evolution of the velocity profiles (including their curvature) with remark-

able accuracy.

Future research will focus on developing and testing a similar model for smooth-to-rough surface transitions. In addition, tests will be performed to assess the potential of the new models to be implemented in surface boundary conditions for large-eddy simulations of boundary layer flow over heterogeneous surfaces. These boundary conditions, used to calculate the local value of the surface shear stress as a function of the velocity, are currently based on direct application of similarity theory (i.e., the log law under neutral stability conditions).

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