MODELAIR – DELIVERABLE

D3.4 – COMPARISON OF NUMERICAL AND EXPERIMENTAL DATABASES AND VALIDATION OF CFD SOLVERS

This report is part of a project that has received funding from the European Union's Horizon Europe MSCA Doctoral Networks 2021 programme under **Grant Agreement No. 101072559**

Deliverable number: D3.4
Due date: 28th February 2025
Type[1]**:** R
Dissemination Level[1]**:** PU
Work Package: WP3
Lead Beneficiary: ULB, UoB
Contributing Beneficiaries: AQC

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[1]

Type	R = Report ADM = Administrative PDE = diss./ex. O = Other DEC = Websites, patents filing, press & media actions, videos, etc.
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Deliverable leader: Emanuele Bombardi, Alessandro Parente, Mahdi Azarpeyvand.

E-mail of lead author: emanuele.bombardi@ulb.be

Reviewer(s): Ben Marner

Version	Date	Description
0.1	29/01/2025	Draft
0.2	08/02/2025	Reviewed
1.0	09/02/2025	**Final version**

Abstract

This study presents the validation of a Computational Fluid Dynamics (CFD) model for the Atmospheric Boundary Layer (ABL) using the SST k-ω turbulence model with a modified wall function. The validation is performed against experimental data from the Bristol Laboratory for Wind Tunnel, where an urban-type boundary layer was generated using the Counihan method. The numerical model employs specifically designed inlet profiles for velocity and turbulent quantities, along with a modified wall function to account for surface roughness effects. Key parameters such as friction velocity and aerodynamic roughness length were determined through experimental data fitting. The results demonstrate excellent agreement with experimental measurements and, crucially, maintain horizontal homogeneity throughout the computational domain. The validated model successfully preserves the prescribed inlet conditions from inlet to outlet, confirming its suitability for generating controlled and reproducible flow conditions necessary for urban flow simulations. This work provides a robust framework for simulating ABL flows, particularly valuable for applications requiring accurate representation of approach flow conditions in urban environments.

Keywords

Atmospheric boundary layer, CFD, Reynold averaged Navier-Stokes (RANS), Boundary conditions and urban flow.

List of Participants

1	COO	Universidad Politécnica de Madrid	UPM	ES
2	BEN	BARCELONA SUPERCOMPUTING CENTER-CENTRO NACIONAL DE SUPERCOMPUTACION	BSC	ES
3	BEN	UNIVERSITE LIBRE DE BRUXELLES	ULB	BE
4	BEN	KUNGLIGA TEKNISKA HOEGSKOLAN	KTH	SE
5	BEN	OVE ARUP & PARTNERS SA	ARUP	ES
6	BEN	MICROFLOWN TECHNOLOGIES BV	MT	NL
7	AP	BuildWind SPRL	BW	BE
8	AP	BRISTOL CITY COUNCIL	BRIS CC	UK
9	AP	AYUNTAMIENTO DE MADRID	AY MAD	ES
10	AP	UNIVERSITY OF BRISTOL	UoB	UK
11	AP	AIR QUALITY CONSULTANTS LTD	AQC	UK

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1. Introduction

The atmospheric boundary layer (ABL) is a fundamental component of the Earth's atmosphere, where most human activities take place. It extends from a few tens of meters to approximately 3 km, depending on weather conditions and surface characteristics. Within the ABL, the atmospheric surface layer (ASL) represents the lowest 10% of the boundary layer, typically extending up to 100 meters above the ground. As the interface between the Earth's surface and the free atmosphere, an accurate representation of the ABL is essential for understanding and predicting atmospheric phenomena.

In computational fluid dynamics (CFD), Reynolds-Averaged Navier-Stokes (RANS) simulations remain the most widely used approach for modelling atmospheric flows, particularly in urban environments, due to their computational efficiency and robust performance in capturing mean flow characteristics. In this context, achieving fully developed equilibrium profiles as the initial state of ABL flow is crucial for simulating urban flows effectively, ensuring controlled and replicable flow conditions. A key requirement for this equilibrium state is horizontal homogeneity, meaning that the mean flow field quantities depend only on height and exhibit no streamwise gradients in mean velocity or turbulence properties. Maintaining horizontal homogeneity requires that the density, height, and distribution of surface roughness elements remain consistent across the upwind area of influence. This assumption simplifies the complex interactions between surface forces and atmospheric dynamics, thereby improving the accuracy and stability of numerical simulations.

As highlighted in prior research, achieving a reliable ABL model requires careful consideration of several factors: the balance of driving shear stress, the treatment of turbulence properties at the top of the domain, the application of appropriate wall functions at the surface, and the selection of inlet velocity and turbulence profiles.

The primary objective of this work is to validate a RANS-based ABL CFD model using the SST k-ω turbulence model and a modified wall function to account for surface roughness, following the work of Parente et al. [2011].

This study focuses on achieving horizontal homogeneity in the simulated ABL by employing a customized turbulence model, optimized boundary conditions, and an appropriate wall treatment. The validation is performed against experimental data from a wind-tunnel-scaled ABL model studied at the Bristol Laboratory for Wind Tunnel (BLWT). By replicating these conditions, the simulation aims to accurately reproduce key ABL characteristics, including velocity profiles and turbulence quantities.

2. CFD model description

The atmospheric boundary layer (ABL) represents a complex and dynamic flow regime that demands sophisticated modeling techniques to accurately capture turbulent flow behavior near the surface. For effective CFD modeling of the ABL, a unidirectional flow approach is typically adopted, simplifying the boundary conditions while maintaining physical accuracy.

The governing equations for horizontally homogeneous and steady ABL balance pressure gradient forces, Coriolis effects, and turbulent stress divergence. In the surface layer, where shear stress variations are negligible, the flow can be treated as having constant shear stress, simplifying the mathematical solution of the conservation equations. The study employs the Shear Stress Transport (SST) k-ω turbulence model, which combines the advantages of k-ϵ and k-ω formulations. The SST k-ω model is particularly effective for simulating wall-bounded flows, including the ABL, as it provides robust treatment of both near-wall turbulence and free shear flows.

2.1. Inlet profiles and turbulence model

Within the surface layer the velocity profile follows the logarithmic law:

$$U = \frac{u_*}{\kappa} \ln\left(\frac{z + z_0}{z_0}\right) \tag{1}$$

This logarithmic profile is derived from the solution to the governing equations assuming homogeneous horizontal flow within a constant shear layer, and its validity has been extensively validated through experimental studies. While alternative formulations like the power law ($U = U_{ref}(z/z_{ref})^{\alpha}$) exist, the logarithmic law provides a more physically consistent representation of the ABL velocity profile, particularly in the surface layer.

The SST k-ω model solves two transport equations: one for turbulent kinetic energy (k) and another for specific dissipation rate (ω). These equations govern the evolution of turbulence in the flow field. For ABL simulations, specific inlet profiles for k and ω and consequent source terms are required to maintain horizontal homogeneity. The inlet profile for turbulent kinetic energy $k(z)$ is given by:

$$k(z) = A\ln\left(\frac{z+z_0}{z_0}\right) + B\left(\frac{z+z_0}{z_0}\right)^2 + C\left(\frac{z+z_0}{z_0}\right) + D \qquad (2)$$

where z is the height above the ground, z_0 is the aerodynamic roughness length, and A,B,C,D are empirical constants that are determined from experimental data. To maintain this K profile throughout the domain, a source term in the K transport equation is required:

$$S_k = -\frac{\partial}{\partial z}\left(v_t\frac{k}{z}\right) = -\frac{u_*\kappa}{z_0}\left(4B\frac{z+z_0}{z_0} + C\right) \qquad (3)$$

The inlet profile for the specific dissipation rate ω is defined as:

$$\omega = \frac{u_*}{\sqrt{\beta^*}}\frac{1}{\kappa\,(z+z_0)} \quad (4)$$

where:

- u_* is the friction velocity, which represents the shear stress at the surface.
- κ is the von Karman constant (approximately 0.41), which characterizes the turbulence near the wall.
- β^* is a model function, given by:

$$\beta^* = \left(\frac{\partial u}{\partial z}\right)^2\frac{1}{\omega^2} = \frac{u_*^4}{k(z)^2} \qquad (5)$$

The inclusion of a functional form for the β^* model parameter is vital for the horizontal homogenous description of the BAL maintaining the turbulence quantities in equilibrium.

The turbulence model parameters are carefully calibrated to ensure that the profile of turbulence intensity and velocity matches experimental observations, with particular attention paid to the wall region where the velocity gradient is steepest.

2.2. Wall treatment: ABL modified wall function

The simulation of the near-wall flow in the ABL requires special treatment due to the strong velocity gradients near the surface. Standard wall functions assume a logarithmic velocity profile, which is commonly used in large-eddy simulations (LES) and Reynolds-averaged Navier-Stokes (RANS) models. However, these wall functions must be adapted to account for surface roughness effects, which are particularly important for the ABL.

To address this, Parente et al. [2011] introduced an alternative near-wall function based on the aerodynamic roughness z_0 rather than the equivalent sand-grain roughness K_S. In the modified wall function G_k is computed at the first cell centroid instead of being integrated over the first cell height as usually done:

$$G_k = \frac{\tau_w^2}{\rho \kappa C_\mu^{0.25} k^{0.5} \left(z + z_0\right)}. \tag{6}$$

This modification enables the prevention of peak production of *k* at the wall. Furthermore, the conventional logarithmic representation of the variable *U* is modified as follows:

$$\frac{U_p}{u_*} = \frac{1}{\kappa} \ln\left(\tilde{E}\tilde{y}^+\right) \tag{7}$$

where:

- U_p is the velocity at the first cell adjacent to the wall, representing the near-wall velocity.
- $y^{\sim+}$is the dimensionless wall distance, defined as:

  $$\tilde{y}^+ = \frac{u_* \left(z + z_0\right)}{\nu} \tag{8}$$

  where *v* is the kinematic viscosity of air.
- $E^{\sim}$ is a constant that accounts for the roughness length z_0, given by:

  $$\tilde{E} = \frac{\nu}{z_0 u_*} \tag{9}$$

The non-dimensional distance $y^{\sim+}$, is derived by adjusting the y^+value based on the aerodynamic roughness. The friction velocity u_*, is not held constant in the longitudinal direction; instead, it is locally computed using the expression $u_* = C_\mu^{0.25} k^{0.5}$. The key innovation of this ABL specific wall function lies in its treatment of surface roughness. It overcomes constraints on minimum height cells near walls, ensuring that near-wall turbulence values are directly computed from the velocity function and its derivatives at the wall.

3. Experimental setup: Bristol laboratory for wind tunnel

The University of Bristol’s Wind Tunnel Laboratory (BLWT) houses a specialized facility designed for atmospheric boundary layer (ABL) studies. The tunnel features a test section measuring 2 meters in width, 1 meter in height, and 18 meters in length, powered by nine axial fans capable of generating flow velocities from 0.5 m/s to 35 m/s. This configuration enables precise control over flow conditions while maintaining low background turbulence levels, essential for accurate ABL simulations.

3.1. Test configurations

The experimental campaign investigated two distinct configurations: an empty test section serving as a baseline configuration, and a modified setup incorporating Counihan method components designed to replicate urban turbulence conditions. The Counihan method implementation includes carefully designed roughness elements and vortex generators that generate a boundary layer exceeding 200 mm in thickness. The setup consists of vortex generators and castellated barriers (height: 900 mm, spacing: 0.6h) and staggered arrays of Lego blocks serving as roughness elements (height: 60 mm, spacing: 140 mm). This arrangement replicates the aerodynamic roughness characteristics typical of urban environments, enabling the simulation of realistic urban boundary layer conditions.

3.2. Instrumentation and data acquisition

Flow measurements were conducted using high-precision hot-wire anemometry, including Dantec 55P15 single-wire probes for mean velocity measurements and Dantec 55P51 crosswire probes for turbulence intensity measurements. The probes were mounted on a linear traverse system, enabling precise spatial positioning throughout the measurement domain. Data acquisition was performed using Labview software at a sampling frequency of 2^{16} Hz.

- Dantec 55P15 single-wire probes for mean velocity measurements
- Dantec 55P51 crosswire probes for turbulence intensity measurements

Measurement durations were optimized to ensure statistical convergence of both mean and turbulent quantities across all measurement locations, providing comprehensive characterization of the flow field under various experimental conditions.

3.3. Flow characterization and validation

Following the experimental setup, comprehensive measurements were conducted to validate the generated atmospheric boundary layer characteristics against established theoretical models and empirical standards. The analysis focused on four key aspects: mean velocity profiles, turbulence intensity, spectral characteristics, and integral length scales. The mean velocity profile was evaluated using the power law formulation:

$$U = U_{\text{ref}}\left(\frac{y-d}{y_{\text{ref}}}\right)^{\alpha} \tag{10}$$

where U_{ref} is the reference velocity, d is the zero-plane displacement, and α is the power law exponent. Analysis revealed α = 0.32 and d = 9.32 mm, values characteristic of urban terrain

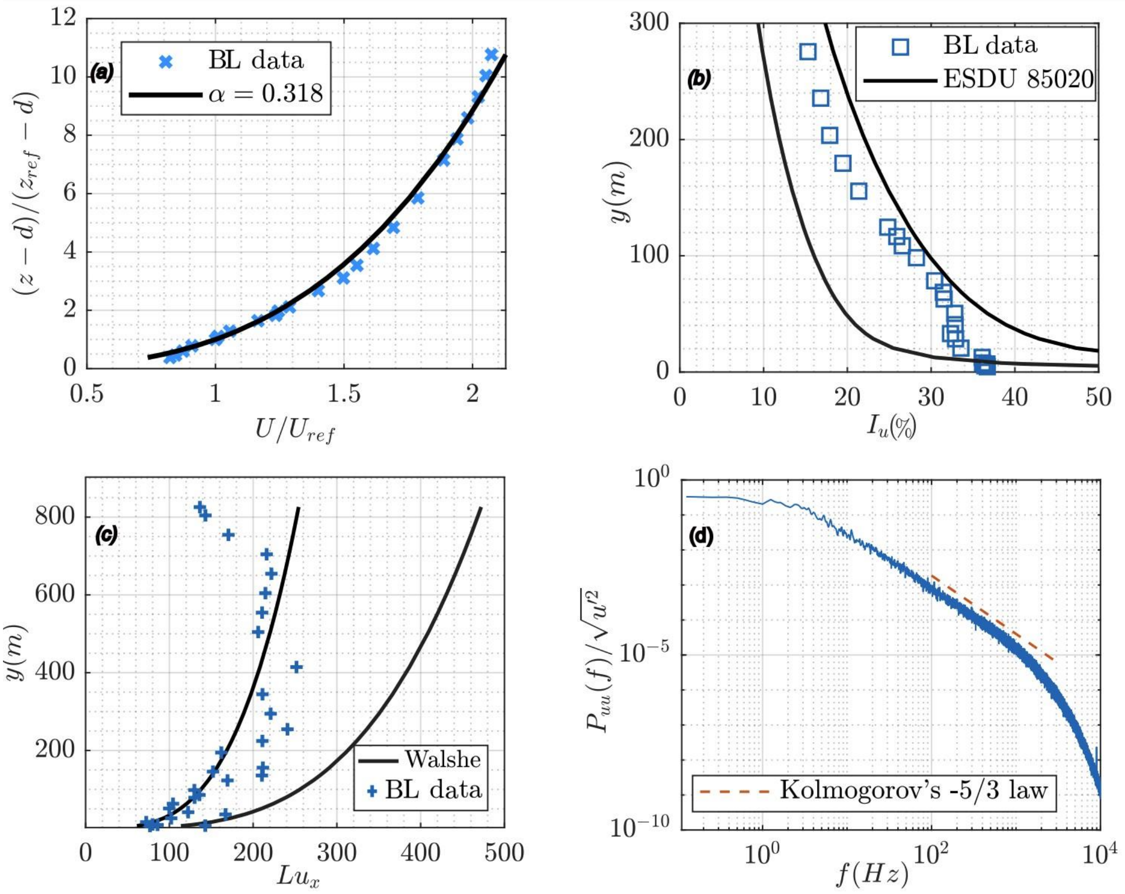

Figure 1: Validation of ABL characteristics: (a) Mean velocity profile with power law fit (α = 0.318), (b) Turbulence intensity within ESDU 85020 confidence bounds (±30%), (c) Full-scale integral length scale Lu_x comparison with Walshe theory, and (d) Power spectral density at y =255 mm and x = 0 mm.

p according to ESDU guidelines (Figure 1(a)). The turbulence intensity, defined as $I_u = u'^2/U$, was found to fall within the 30% confidence interval specified by ESDU 85020 standards for heights up to 300 meters in full scale (Figure 1b).

Spectral analysis of the longitudinal velocity fluctuations, performed at y = 255 mm, demonstrated clear evidence of an inertial subrange with the characteristic -5/3 slope in the power spectral density $P_{uu}(f)$ (Figure 1(d)). This behavior, consistent with Kolmogorov's theory of turbulence, confirms the presence of a fully developed turbulent flow regime. Additionally, integral length scales L_{ux} were computed using autocorrelation functions based on Taylor's hypothesis. The calculated scales showed good agreement with Walshe's theoretical predictions, falling within the accepted 30% variation range for urban ABLs.

To establish appropriate scaling for urban flow applications, Cook's method was employed:

$$S = \frac{91.3(y-d)^{0.491}}{L_{u_x}^{1.403} y_0^{0.088}} \tag{11}$$

where y_0 represents the roughness length. The integral length scale L_{ux} was determined by fitting measured data to Cook's design curve using the relationship $f\,\frac{L_{ux}}{U} = 1$, where f is the lowest measured frequency (Figure 1(c)). This analysis established a scaling factor of 1:800 for urban flow simulation.

These comprehensive measurements validate the wind tunnel's capability to generate realistic urban ABL conditions, providing a reliable foundation for subsequent urban flow studies. The close agreement with theoretical predictions and established standards across multiple flow parameters demonstrates the robustness of the experimental setup.

4. Results and discussion

4.1. Model validation framework

The validation of the atmospheric boundary layer (ABL) model encompasses two primary aspects: comparison with experimental data and assessment of horizontal homogeneity. The computational setup was designed to replicate the wind tunnel conditions as accurately as possible, utilizing a two-dimensional domain with dimensions matching the test section (18 m length × 1 m height). The domain was discretized using a structured grid of 1800 × 71 cells, with vertical stretching to ensure adequate resolution of near-wall gradients. The first cell centroid was positioned at 0.005 m above the surface, crucial for accurate resolution of the wall-adjacent region.

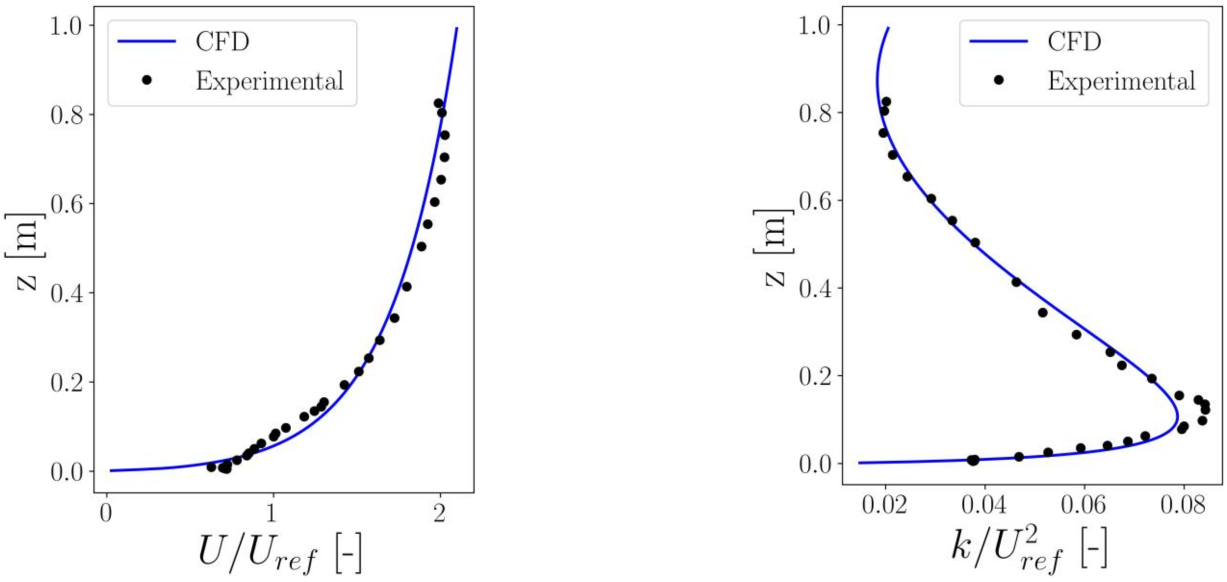

Figure 2: Comparison between CFD inlet profiles and experimental data for normalized streamwise velocity (left, a) and normalized turbulent kinetic energy (right, b).

4.2. Boundary conditions and numerical setup

The simulation employed carefully defined boundary conditions based on the HHABL theoretical analysis:

- Inlet: Prescribed profiles for velocity *U*, turbulent kinetic energy *k*, and specific dissipation rate *ω*
- Outlet: Pressure outlet condition with minimal backflow
- Upper boundary: Constant shear stress condition following Richards and Hoxey [1993] recommendations
- Ground surface: ABL modified wall function

The numerical solution utilized OpenFOAM's pressure-based solver with second-order discretization schemes for momentum and turbulence quantities. The SIMPLE algorithm ensured stable pressure-velocity coupling, with convergence monitored through residual reduction of at least six orders of magnitude.

The friction velocity ($u_* = 0.979$ m/s) and aerodynamic roughness length ($z_0 = 4.89 \cdot 10^{-3}$ m) were determined through interpolation of experimental velocity profiles from the logarithmic law fitting. This approach ensured accurate representation of the surface layer characteristics and provided essential parameters for the wall function implementation.

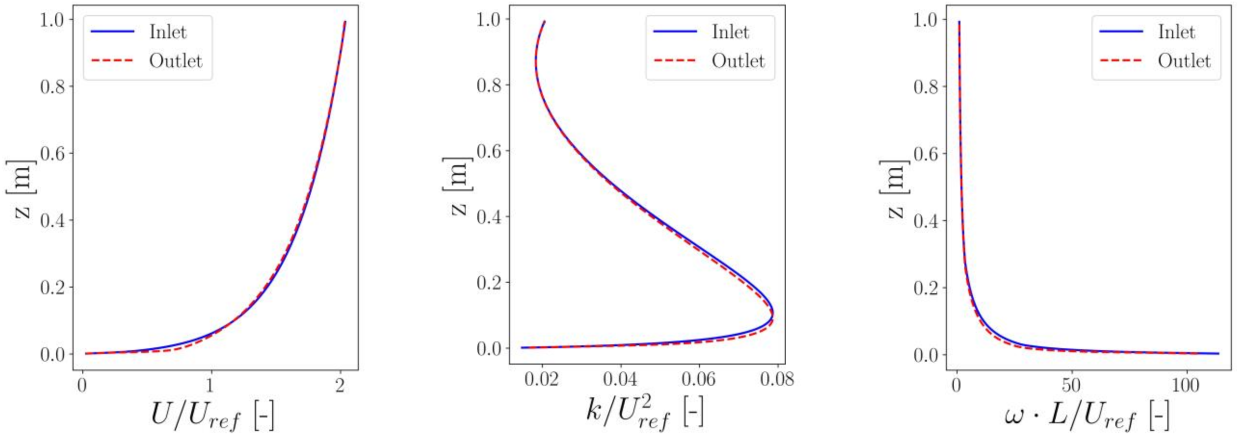

Figure 3: Comparison between CFD inlet and outlet profiles for normalized streamwise velocity (left, a), normalized turbulent kinetic energy (center, b) and normalized specific dissipation rate (right, c).

4.3. Velocity profile validation

Figure 2a presents the comparison between the inlet velocity profile and experimental data, from which the friction velocity ($u_* = 0.979$ m/s) and aerodynamic roughness length ($z_0 = 4.89 \cdot 10^{-3}$m) were determined through profile fitting. Using these parameters, the model predictions were evaluated throughout the domain, as shown in Figure 3a, where simulated velocity profiles at the inlet and outlet of the domain are compared. The results demonstrate excellent agreement throughout the domain height and the logarithmic profile is well-maintained, indicating proper implementation of the wall function and accurate representation of surface roughness effects.

4.4. Turbulent kinetic energy distribution

The turbulent kinetic energy inlet profile was fitted to the experimental data using Equation 2, as shown in Figure 2b. The fitting process identified the following empirical constants: A = 1.312, B = $1.599 \cdot 10^{-4}$, C = -0.0647, and D = 0.359. These parameters ensure accurate representation of the turbulence structure at the inlet. The turbulent kinetic energy profiles throughout the domain, shown in Figure 3b, exhibit good agreement with experimental data. The model accurately captures the characteristic peak near the surface and the gradual decrease with height. The maintenance of the k profile along the domain length indicates proper balance between production and dissipation terms, facilitated by the implemented source term in the k-equation.

4.5. Specific dissipation rate profile

The specific dissipation rate (ω) profiles, illustrated in Figure 3c, show consistent behavior throughout the domain. While direct experimental comparison was not available for ω, the profiles maintain the expected theoretical behavior and support the overall turbulence structure of the ABL.

4.6. Overall model performance

A critical aspect of the validation is the maintenance of horizontal homogeneity throughout the domain. Analysis of the flow field demonstrates negligible streamwise gradients in both mean and turbulent quantities, confirming the model's ability to maintain equilibrium conditions. This is evidenced by consistent velocity profiles at different streamwise locations, stable turbulent kinetic energy distribution throughout the domain, and well-maintained specific dissipation rate profiles. The preservation of horizontal homogeneity validates the model's capability to generate controlled flow conditions without artificial acceleration or deceleration, a crucial requirement for accurate ABL simulation. These results demonstrate the model's suitability for applications requiring accurate representation of ABL characteristics, particularly in urban flow simulations where proper representation of the approach flow is crucial.

5. Conclusions

This study has presented a comprehensive validation of an atmospheric boundary layer (ABL) model using the SST k-ω turbulence model with a modified wall function. The validation was performed against experimental data from the Bristol Laboratory for Wind Tunnel, providing a robust benchmark for computational fluid dynamics (CFD) simulations of urban flows. The implemented model successfully reproduces key characteristics of the ABL, as demonstrated through:

- Accurate prediction of the logarithmic velocity profile, validated through experimental comparison

- Proper representation of turbulent kinetic energy distribution, with correctly captured nearwall behavior
- Achievement of horizontal homogeneity, evidenced by the preservation of flow properties between inlet and outlet
- Effective implementation of surface roughness effects through a modified wall function

The maintenance of horizontal homogeneity throughout the computational domain is particularly significant for urban flow simulations. This characteristic ensures that any changes in flow patterns observed in subsequent urban studies can be attributed solely to the presence of urban structures rather than numerical artifacts or upstream flow development. The model's ability to maintain consistent profiles of velocity and turbulent quantities between inlet and outlet demonstrates its suitability for generating controlled and reproducible flow conditions.

This validation study underscores the importance of properly modeling the ABL as horizontally homogeneous for urban flow applications. Without such homogeneity, variations in approach flow conditions could introduce uncertainties in the simulation results, making it difficult to isolate the effects of urban geometries on flow patterns. The validated model thus provides a reliable foundation for future studies of urban flows, ensuring that the simulated atmospheric conditions remain consistent and physically accurate throughout the computational domain.

Acknowledgements

This project has received funding from the European Union's Horizon Europe research and innovation program under the MODELAIR project grant agreement No.101072559.

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