EACWE 2025 Trondheim

Indoor-outdoor pollutant transport through a hollow cube with a cross-ventilating flow

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SUMMARY:
Cross-ventilation plays a critical role in dispersing indoor pollutants by promoting the exchange of indoor and outdoor air. To investigate pollutant transport in such scenarios, we experimentally investigate the flow through a hollow cube immersed in an atmospheric boundary layer as an idealized representation, with a ground-level passive scalar (pollutant) source placed at the centre of the building. The focus is on characterizing the velocity and concentration fields to understand the scalar transport mechanisms within and outside the cube. Two different experiments are conducted comparing results from the University of Surrey EnFlo wind tunnel and the University of Southampton water tunnel. The wind tunnel experiments used a laser Doppler anemometer (LDA) and a Fast flame ionization detector (FFID) to collect point measurements of the velocity and concentration, respectively. The water tunnel experiments used Planar Laser-Induced Fluorescence (PLIF) and Particle Image Velocimetry (PIV) to obtain simultaneous measurements of scalar and flow fields. The insights gained from this study can potentially improve our understanding and help model pollutant exchange between indoor and outdoor environments, especially in complex atmospheric boundary layer conditions.

Keywords: Air pollution, Outdoor dispersion, Scalar dispersion, Cross-ventilation.

1. INTRODUCTION

In urban environments, pollutants can originate from both indoor and outdoor sources. Consequently, when it comes to modelling pollutant dispersion, numerous studies have concentrated on scalar dispersion in outdoor environments (e.g., Lim et al. (2022)) as well as indoor environments (e.g., Biswas and Vanderwel (2024a), Biswas and Vanderwel (2024b), and Tominaga and Blocken (2016)). The indoor environment poses health challenges due to various sources of pollutants, such as volatile organic compounds and particulate matter and could be life-threatening in cases such as potential gas leaks and airborne transmission of infectious diseases. Since humans spend most of their time indoors, maintaining a healthy and sustainable indoor environment would be very critical for human health. In such scenarios, cross-ventilation could help to keep a healthy indoor environment (Finnegan et al., 1984).

To date, most experimental studies on flow and pollutant dispersion for outdoor and indoor environments predominantly utilize wind tunnel facilities, while the use of water tunnels for similar studies remains relatively limited. Drawing motivation from this, we perform a series of experiments examining pollutant transport in a cross-ventilating flow through a scaled-down hollow building (a hollow cube) in a water tunnel with an indoor scalar (Rhodamine dye) source (Fig. 1(a)). Subsequently, the findings are compared with sets of analogous experiments performed in

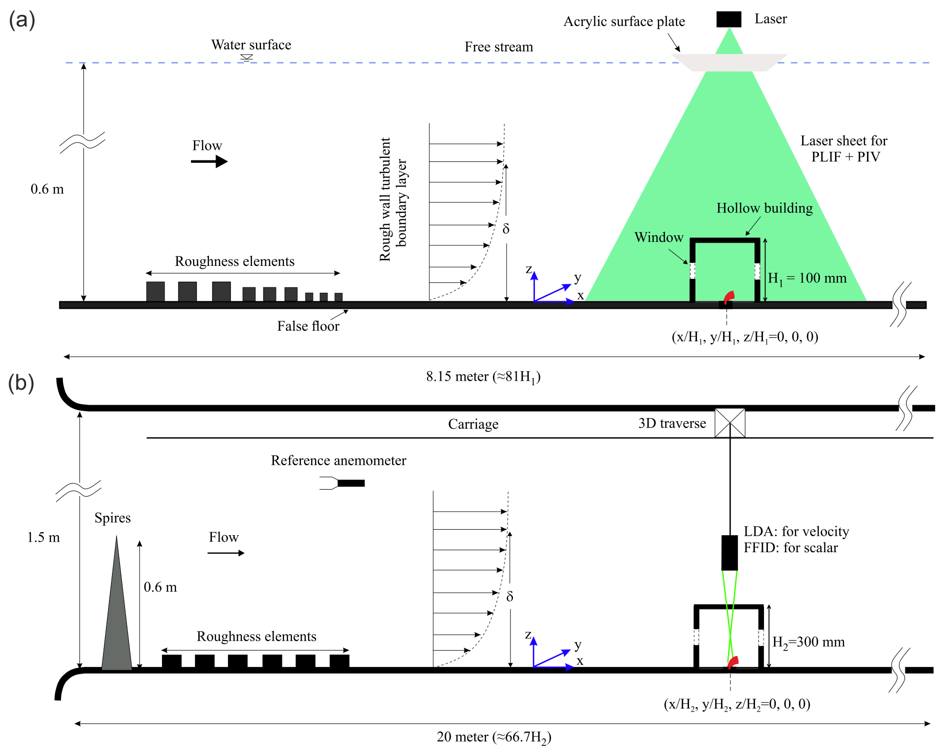

Figure 1. Schematic of the experimental setups showing the hollow building inside the turbulent boundary layer inside (a) water flume facility and (b) wind tunnel facility.

a wind tunnel, with the model building being equipped with an indoor gaseous (Propane) scalar source (Fig. 1(b)). Our comparative approach aims to establish the consistency and reliability of dispersion measurements across two experimental arrangements by evaluating and comparing the flow dynamics and scalar dispersion.

2. EXPERIMENTAL METHODOLOGY

Two different experiments were conducted and then compared results from the University of Southampton water tunnel (see Fig. 1(a)) and the University of Surrey EnFlo wind tunnel (Fig. 1(b)). The condition of a turbulent atmospheric boundary layer was created using a series of roughness elements placed upstream as shown in Fig. 1 (for details, see Biswas, Hayden, et al. (2024) and Biswas and Vanderwel (2024b)).

The water tunnel experiments involved a cube of height H_1 = 100 mm (approximately 40:1 to full scale) with a reference water speed at the cube height of $U_{Ref,1}$ = 0.45 m/s, resulting in a Reynolds number of $Re = U_{Ref,1}H_1/\nu_{water} \approx$ 50,000. The wind tunnel experiments were performed using a cube of height H_2 = 300 mm (approximately 13:1 scale to full-scale) with a reference wind speed at the cube height of $U_{Ref,2}$ = 2.5 m/s, resulting in the $Re(= U_{Ref,2}H_2/\nu_{air})$ being the same as in the water tunnel. Both setups benefited from spires and roughness to condition the oncoming boundary layer to have a depth of $\delta/H \approx$3 (H=cube height). The hollow (acrylic) cubes had two opposite openings ($0.35H \times 0.35H$) in the windward and leeward façade, with about 10% area-based porosity (as in Biswas and Vanderwel (2024a)).

2.1. Water tunnel setup

In the water tunnel, Rhodamine 6G dye is injected from a ground-level source at the centre of the model, with negligible effects on the flow (similar to Biswas and Vanderwel (2024a)). The aqueous solution of the dye with concentrations (C_S) of 1 mg/L was injected at a constant flow rate of Q_S=7 mL min^{-1} (see Fig. 1(a)). The two-dimensional maps of the velocity (U) and the scalar concentration (C), within the cube were captured simultaneously through Particle Image Velocimetry (PIV) and Planar Laser-Induced Fluorescence (PLIF), in the streamwise plane (x-z) along the centreline of the building. For the PIV measurements, the flow was seeded with 50 μm polyamide seeding particles. For both the PIV and PLIF measurements, the illumination was provided by a 100 mJ Nd:YAG double-pulsed laser with an emission wavelength of 532 nm, and appropriate filters were used in two cameras to separate the PIV and PLIF signals.

2.2. Wind tunnel setup

The EnFlo wind tunnel facility (see Fig. 1(b)) at the University of Surrey (Placidi et al., 2023) is a suction tunnel with a large working section measuring 20m in length, 3.5m in width, and 1.5m in height. The flow was seeded with micron-sized sugar particles, and the flow velocity was measured using a Dantec two-component laser Doppler anemometer (LDA). For scalar, a mixture of Propane gas and air was used as the tracer, released from ground level. The flow rate of the gas mixture (Q_S) was about 0.021 l min^{-1}, at a concentration (C_S) of about 15,000 ppm. Tracer concentration measurements were performed using a Cambustion Fast Flame Ionization Detector (FFID) with a frequency response of 200 Hz.

3. RESULTS AND DISCUSSIONS

The results from the water tunnel measurements are compared with the wind tunnel (Figs. 2(b,c,d)), in terms of the wall-normal (z/H) profiles for the mean velocity, scalar and variance at different locations as illustrated in Fig. 2(a). The magnitude and the wall-normal variation in velocity and the scalar measured at these locations along the streamwise centre plane are found to be substantially similar [Figs. 2(b,c,d)] across the water tunnel and wind tunnel, thus establishing universality in the methodologies and measured quantities. To help quantify the out-of-plane variations in $\overline{C}$, the wind-tunnel measurements performed at two out-of-plane locations clearly show [Figure 2(c(ii))] a lower scalar buildup than the centre plane and the nearly uniform wall-normal (z/H) scalar concentration implies a relatively well-mixed scalar in these regions in comparison with the centre plane.

4. CONCLUSION

To summarise, the present work experimentally investigated a cross-ventilating flow through a hollow cube with an indoor scalar source, immersed in a rough-wall turbulent boundary layer. The primary focus was on comparing the water tunnel PIV and PLIF measurements for indoor velocity and velocity, with the wind tunnel measurements using LDA and FFID. The in-plane scalar (dye) field from the water tunnel shows scalar accumulation in re-circulation regions, with the peak concentration being around the source and the upstream near-ground corner. These magnitudes of water velocity and scalar concentration and their spatial variations are considerably close to the air velocity and gas concentration from wind tunnel experiments.

The substantial similarities in the results obtained from both water tunnel and wind tunnel experiments affirm the validity and reliability of both experimental setups in simulating the scalar

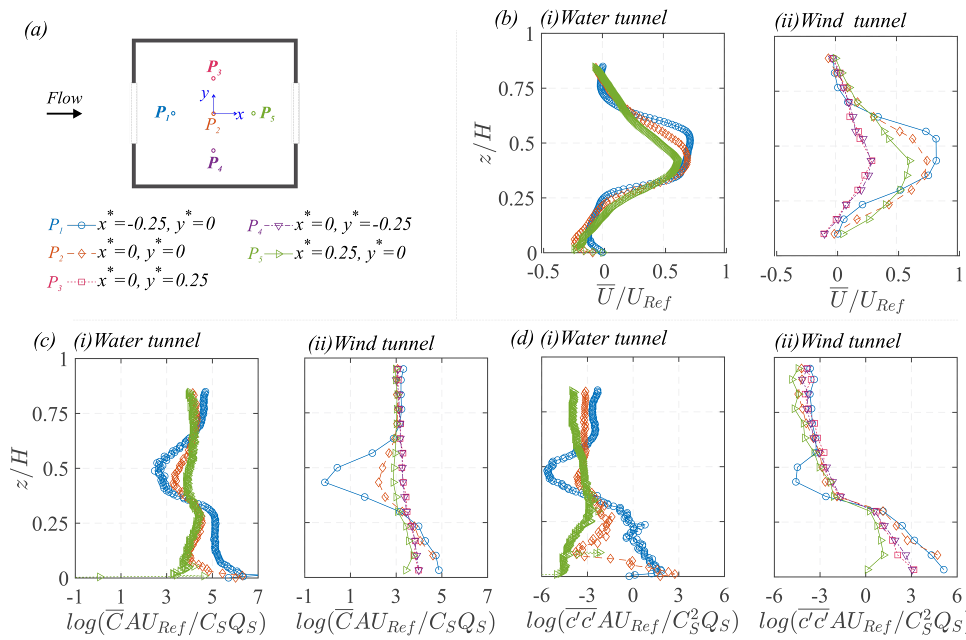

Figure 2. (a) A top-view schematic (x-y plane) showing the x-y coordinates of the different indoor locations (P_1 to P_5) where the wall-normal (z/H) profiles for indoor velocity and concentration are obtained; here, $x^* = x/H$, $y^* = y/H$ and $z^* = z/H$. (b,c,d) Wall-normal (z/H) profiles of the indoor mean stream-wise velocity ($\overline{U}/U_{Ref}$), mean concentration ($\overline{C}AU_{Ref}/C_SQ_S$) and concentration variance ($\overline{c'^2}/C_S^2$), at different locations, as illustrated in 'a'. In 'b, c & d', the water tunnel and wind tunnel measurements are shown in 'i' and 'ii', respectively.

dispersion in such urban flows with reasonable accuracy. This gives us confidence in the use of both wind tunnel and water tunnel methodologies as complimentary experimental approaches for studying pollutant dispersion in complex atmospheric boundary layer conditions.

ACKNOWLEDGEMENTS

Many thanks to Youssef Elashmawi, Tomos Rich and Dominic Clements for helping with the water tunnel experiments and to Paul Hayden for helping with the wind tunnel experiments. We gratefully acknowledge the funding from CV's UKRI Future Leaders Fellowship (MR/S015566/1).

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