Pollutant dispersion in a cross-ventilating flow through a scaled building: Wind and water tunnel measurements

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1 INTRODUCTION

In urban environments, pollutants can originate from both indoor and outdoor sources [1]. Consequently, when it comes to modelling pollutant dispersion, numerous studies have concentrated on scalar dispersion in outdoor environments (e.g., [2]) as well as indoor environments (e.g., [3, 4, 5]). 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 [6].

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. Subsequently, the findings are compared with sets of analogous experiments performed in a *wind tunnel*, with the model building being equipped with an indoor gaseous (Propane) scalar source. 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 Figure 1(a)) and the University of Surrey EnFlo wind tunnel (Figure 1(b)). The condition of a turbulent atmospheric boundary layer was created using a series of roughness elements placed upstream as shown in Figure 1 (for details, see [2, 7]).

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 $Re = U_{Ref,1} H_1/\nu \approx 50{,}000$; here, $U_{Ref,1}$ is the oncoming mean streamwise velocity at the cube's height, measured without the cube in the test section. On the other hand, the wind tunnel experiments were performed using a hollow cube of height H_2 = 300 mm (approximately 13:1 scale to a full-scale room) with a reference wind speed at the cube height of $U_{Ref,2}$ = 2.5 m/s, resulting in the Re ($=U_{Ref,2} H_2/\nu$) 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 x 0.35H) in the windward and leeward façade, with about 10% area-based porosity (see Figure 2(a)). Before beginning experiments involving the cube, the incoming boundary layer was characterized without the model in the test section, as shown in Figure 2(b) are the wall-normal (z/H) profiles of the normalised mean stream-wise velocity ($\overline{U}/U_{Ref}$) from both the experimental facilities; here, $\overline{U}$ is the time-averaged stream-wise velocity.

2.1 Water tunnel measurements

The water tunnel setup facilitated *Rhodamine 6G dye* injection at the floor of the building, essentially replicating a ground-level passive scalar source with negligible effects on the flow (similar to [2, 4]). The aqueous solution of the dye (Schmidt number, Sc=2500±300) with concentrations (C_S) of 1 mg/L was injected at a constant flow rate of Q_S=7 mL min^{-1} (see Figure 1(a)). The two-dimensional maps of the

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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 $50\ \mu m$ 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.

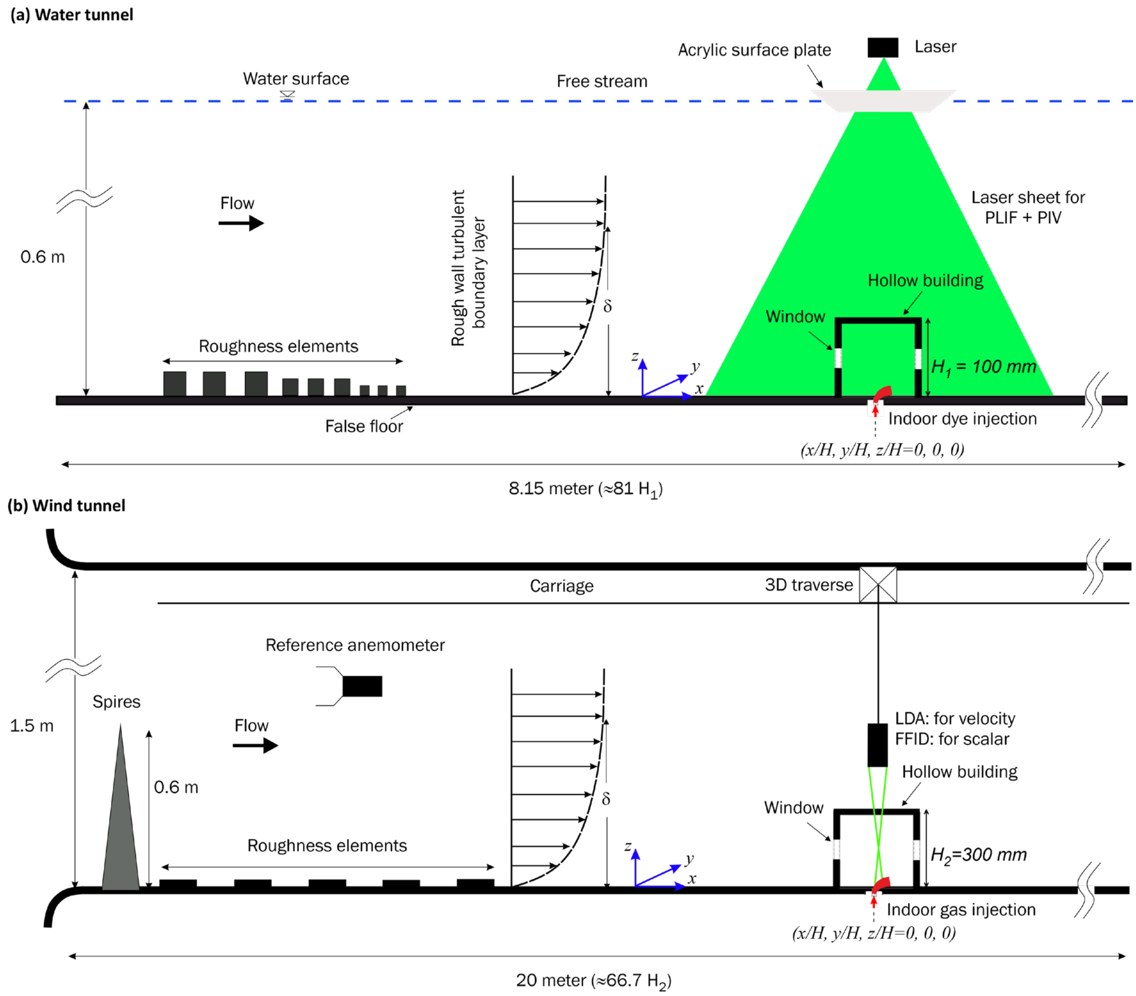

Figure 1. *(a) Schematic of the side-view of the experimental setups showing the hollow building inside the turbulent boundary layer in: (a) the water flume facility at the University of Southampton, and (b) the Enflo wind tunnel facility at the University of Surrey.*

2.2 Wind tunnel setup

The *EnFlo* wind tunnel facility (see Figure 1(b)) at the University of Surrey [7] is a suck-down 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 ($Sc \approx 1.5$), 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

Turbulent flows around cubes are characterized by phenomena like separation, re-circulation, and vortex shedding. Introducing openings in such configurations results in an unsteady internal flow. In the present configuration, the internal flow involves a jet penetrating the cube and two re-circulation regions (R_{up}, R_{low}) adjacent to the upper and lower walls, as delineated in Figure 3(a) showing the streamwise time-averaged velocity ($\overline{U}/U_{Ref}$) in the centre-plane (x-z), from water tunnel measurements. Following this,

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the scalar concentration map ($C^* = \overline{C}\,AU_{Ref}/C_SQ_S$; here, $A=H^2$) in Figure 3(b) shows a notable accumulation of scalar in the re-circulation regions near the top and bottom walls of the cube, with relatively higher scalar strength near the bottom wall; here, C and $\overline{C}$ are the instantaneous and time-averaged scalar concentrations.

The results from the water tunnel measurements are compared with the wind tunnel (Figure 4(b,c,d)), in terms of the wall-normal (z/H) profiles for the mean velocity, scalar and variance ($\overline{c'c'}AU_{Ref}/C^2_SQ_S$; here, $c'=C-\overline{C}$), at different locations (P_1, P_2 & P_5) as illustrated in Figure 4(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 [Figure 4(b,c,d)] across the water tunnel and wind tunnel, thus establishing universality in the methodologies and measured quantities. In addition, be noted that the present water tunnel measurements have been performed only in the centre plane. To help quantify the out-of-plane variations in $\overline{C}$, the wind-tunnel measurements performed at two out-of-plane locations (P_3 & P_4) clearly show [Figure 4(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.

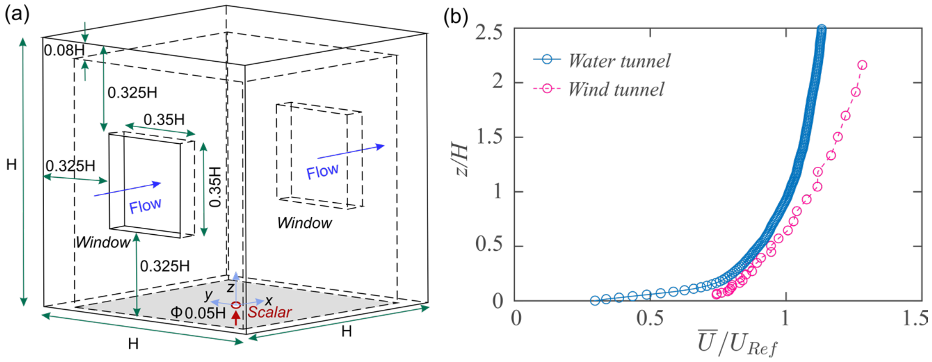

Figure 2 (a) Schematic showing the 3D view of the hollow building model. The dye is injected from a hole flush mounted at the centre of the floor (x/H,y/H,z/H=0,0,0). (b) The base flow mean stream-wise velocity ($\overline{\mathbf{U}}/\mathbf{U_{Ref}}$) is shown along the wall-normal direction (z/H), measured in the water and wind tunnel test section (at x/H=-1, y/H=0) without the cube.

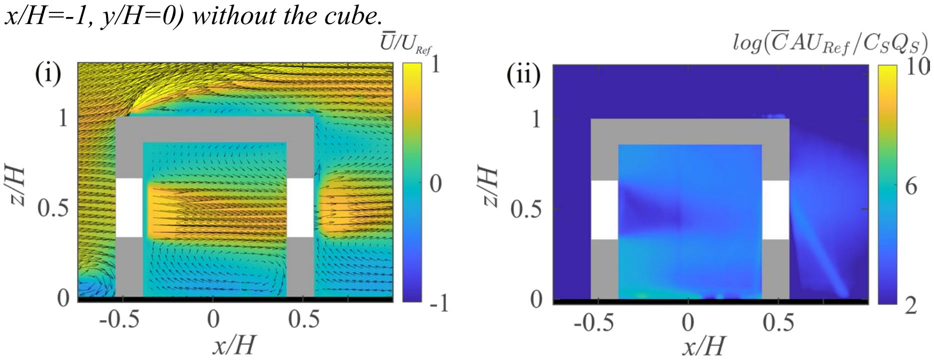

Figure 3. Time-averaged (a) vector map in the streamwise centre plane (x-z) overlaid with streamwise velocity ($\overline{\mathbf{U}}/\mathbf{U_{Ref}}$), and (b) scalar concentration map ($\overline{\mathbf{C}}AU_{Ref}/C_SQ_S$, in natural logarithmic scale), all obtained in the water tunnel. Flow is from left to right.

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 (dye) and their spatial variations are considerably close to the air velocity and gas concentration from wind tunnel experiments.

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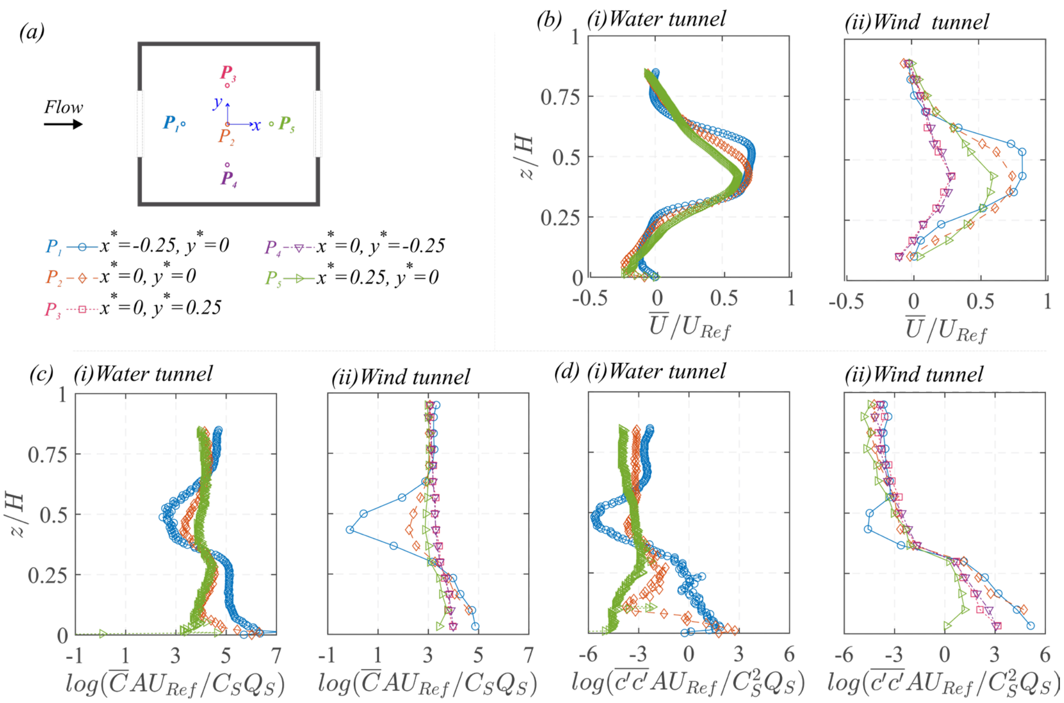

Figure 4. (a) A top-view schematic (x-y plane) showing the x-y coordinates of the different indoor locations (P_1 to P_5) where the wall-normal (z/H) profiles for indoor velocity and concentration are obtained; here, x=x/H, y*=y/H and z*=z/H. (b,c,d) Wall-normal (z/H) profiles of the indoor mean stream-wise velocity ($\overline{U}/U_{Ref}$), mean concentration ($\overline{C}AU_{Ref}/C_SQ_S$) and concentration variance ($\overline{c'c'}AU_{Ref}/C^2{}_SQ_S$), 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.*

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 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.

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