City breathability as quantified by the exchange velocity and its spatial variation in real inhomogeneous urban geometries: An example from central London urban area

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1. Introduction

Being in an era of extreme technological advancement and densely populated cities, environmental concerns have been raised with regard to urban air quality as well as energy efficiency and pedestrian thermal comfort. Critical roles to these environmental and life qualities play the wind flow over and through a city and the capacity of a city to ‘ventilate’ itself. In the city the wind flow directly affects air quality through transport and dispersion of the pollution within its street network, road intersections and building fabric. The term ‘city breathability’ was first introduced by Neophytou and Britter, 2005 as a dynamic characteristic parameter reflecting the potential of a city to ventilate itself by removing and diluting pollutants, heat, moisture and other scalars. In building ventilation concepts, ventilation is the process of exchange of indoor air with outdoor air through this process, any pollutant emission indoors can be diluted and removed. If the building packing density of the surrounding neighbourhood in which the building belongs is large, then there will be a reduction in pressure difference across the buildings, thus limiting the possibility of natural ventilation.
Several studies have been carried out over the last decade in order to address the pollution dispersion within urban areas, street canyons and intersections as well as its multi-scale nature (e.g. Britter and Hanna, 2003; Vardoulakis et al., 2003; Barlow et al., 2004; Dobre et al., 2005; Wang and Zang, 2009; and Wanga et al., 2009). More detailed studies recently have analysed the role of various urban features such as the building packing density (e.g. Belcher et al., 2003; Cheng et al., 2007; and Blocken et al., 2008; Davidson et al., 1996), the street width, building height, roof geometry, and wind speed and direction (e.g. Berkowicz et al., 2006; Di Sabatino et al., 2007; Di Sabatino et al., 2008; Huang et al., 2009; Hang et al., 2009; Soullac et al., 2008; and Markides et al., 2010), tree planting (e.g. Gromke et al., 2008 and Buccolieri et al., 2009), as well as the coupling effects of atmospheric chemistry (Neophytou et al., 2004; Neophytou et al., 2005). In the scope of operational modelling, studies have been carried out to investigate the wind flow in idealised urban settings and its comparative modelling with Computational Fluid Dynamics (CFD) and integral models (Di Sabatino et al., 2007; Di Sabatino et al., 2008; Huang et al., 2008). Additionally, the need for operational tools has been created for cases of accidental release of hazardous materials where emergency authorities and civil defence personnel will need to employ such tools in order to determine their course of action (Neophytou et al., 2011). Recently there has been increased concern as well about the non-accidental release of hazardous materials in urban areas (Britter and Hanna, 2003). This work derives from an extensive concerted effort in the UK on Dispersion of Air Pollutants and their Penetration to the Local Environment – the DAPPLE project (e.g. Arnold et al., 2004) – encompassing an extensive series of field measurement studies (e.g. Wood et al. (2009), Shallcross et al. (2009), and Martin et al. (2010a, 2010b)), wind tunnel experiments (e.g. Robins et al. (2010) and computational simulations (Xie and Castro, 2009).

### 1.1. Exchange velocity and city breathability

The wind flow over a city and its interaction with the urban obstacles results in complex flow patterns. Urban obstacles exert a relatively large resistance force on the wind flow and as a result the flow rate exiting a city is less than the flow upstream. The flow interaction between flow within the canopy and the overlying flow above the buildings is a mass flow exchange process which results in a momentum flux exchange. Exchange velocity can be defined either by the average velocity of mass transfer into or out of the urban canopy at a plane of interface between the in-canopy and above-canopy flows, or by the momentum flux transfer process within a control volume. This momentum flux exchange is balanced by the drag force exerted on the buildings which is also associated with the local wall shear stress. The concept of exchange velocity was introduced as a measure of city ventilation by Bentham and Britter (2003); it was later studied with numerical simulations by Hamlyn and Britter (2005), Solazzo and Britter (2002), Cheng and Castro (2002) and Buccolieri et al. (2010) and with experimental methods by Caton et al. (2003), Barlow et al. (2004), Salizzoni et al. (2009) and Markides et al. 2010. For a passive, neutrally-buoyant, tracer (massless) contaminant, this exchange velocity directly relates to the rate of removal of the contaminant and thereby the breathability capacity.

The equation below illustrates how this exchange velocity is related to the net input (or removal) rate of a contaminant with concentration $C$ within the street canyon (considered as a control volume) of volume $V$, a background concentration of pollutant (i.e. above the canyon) of $C_0$, area of exchange $A$, and the exchange velocity of the contaminant $U_t$:

$$
\frac{dC}{dt} = \frac{U_t A C_0}{V} - \frac{U_t A C}{V}.
$$

(Nishizawa et al., 2008). This pollutant dilution or removal capacity is expressed by the ventilation flow rate. In the case of an urban atmosphere, however, the exchange is between flows that both occur in the open urban atmosphere, that of the in-canopy flow and that above the canopy, diluting and removing any emissions (pollutants or heat) from the urban open space; there is no clear distinctive boundary between the two flows and the process resembles more that of breathing or a living organism — hence the term city breathability.

This breathability capacity itself is directly related to the air flow patterns in between building blocks and streets resulting from the interaction between the approaching (to city) atmospheric flow and the city building blocks; such complicated airflow patterns may be stagnant zones and wake regions between buildings and along streets. It is known that, in some cases, street networks have a specific flow capacity, that is the flow rate along a street canyon will attain a constant value (see Soullac et al. (2008) and Hang et al. (2010)) corresponding to some minimum level of breathability (Buccolieri et al., 2010). Moreover, the breathability of an urban area can also be interpreted as a measure of the drag force on the buildings by the wind flow. When the shear stress on the building rooftops is counterbalanced by the opposing shear stress on the street canyon sides it is said that the canyon has reached its capacity in regard to the maximum flow rate it can attain (Hang et al., 2010). In a more recent study, Hang et al. (2012) analysed the contribution of mean flow and turbulence to city breathability within urban canopy layers (at neighbourhood and city scales) using Computational Fluid Dynamics (CFD) simulations. The geometry consisted of several idealised long streets flanked by tall buildings with the wind flow parallel to the street axis. It was found that for neighbourhood-scale models, pollutant removal is mainly associated to mean flow along the streets and breathability improves in streets flanked by taller building, while in city-scale models, pollutant removal due to turbulent fluctuations across street roofs competes with that due to mean flows along the street and thereby breathability improves in streets flanked by lower buildings. An approach using building ventilation ideas most commonly used in indoor environments has been also recently used to determine the pollutant dilution rate in an outdoor urban environment (e.g. Bady et al., 2008; Bu et al., 2009 and Hang et al., 2012).

### Nomenclature

- $A_C$: Surface area of top of control volume
- $A_f$: Building frontal area
- $A_p$: Building plan (rooftop) area
- $A_l$: Building lot area ($A_p + \text{half canyons around building}$)
- $d$: Surface displacement length
- $F_p$: Pressure force
- $H$: Building height (canopy line)
- $H_m$: Average building height of the urban area
- $S$: Surface area of plane
- TKE: Turbulent kinetic energy
- $u$: Mean horizontal velocity in the x-direction
- $u_*$: Friction velocity defined by surface shear stress (averaged over the urban surface)
- $\overline{u'w'}$: Reynolds’ stresses or turbulent momentum fluxes
- $U_C$: In-canopy velocity
- $U_{ref}$: Reference velocity
- $U_E$: Exchange velocity
- $U_{in}$: Inlet velocity
- $w$: Mean vertical velocity in the z-direction
- $z_0$: Surface roughness length
- $A_p$: Plan area density ($= A_p/A_f$
- $A_l$: Frontal area density ($= A_l/A_f$)

### Tke Turbulent kinetic energy

- $\lambda$: Friction velocity derived from an extensive consorted effort in the UK on Dispersion of Air Pollutants and their Penetration to the Local Environment – the DAPPLE project (e.g. Arnold et al., 2004) – encompassing an extensive series of field measurement studies (e.g. Wood et al. (2009), Shallcross et al. (2009), and Martin et al. (2010a, 2010b)), wind tunnel experiments (e.g. Robins et al. (2010) and computational simulations (Xie and Castro, 2009).
If the background concentration of the pollutant generated within the canyon is considered negligible then the exchange velocity directly relates to the net rate of pollutant removal as:

\[
d\frac{C}{dt} = -\frac{Uesan AC}{V}.
\] (1b)

The exchange velocity is also relevant to determine the momentum transport to the canopy, which counterbalances the drag from obstacles and for removal of pollutant or heat from the canopy (following as well Hamlyn and Britter, 2005). It should be possible to relate the momentum flux across a plane to exchange velocity if a reference velocity above and below the canopy top can be defined. This reference velocity for the flow above the buildings was specified at a height of 2.5 times the building height \((H)\) (Hamlyn and Britter, 2005). The reference height of this magnitude is chosen sufficiently above the rooftops where the value of the velocity is closer to the free stream wind velocity value. However, at what height this reference should be exactly taken is still an open question, as in fact it also relates to the roughness sublayer thickness/height which scales both with the packing density of the urban site and the average building height.

The wind boundary layer profile in a city can be treated by standard atmospheric formulas (Stull, 1997), as long as the mean building height is small compared to the surface boundary-layer depth (approximately 100–200 m) and the surface has some statistical homogeneity. The surface shear stress (averaged over the urban surface) defines a friction velocity, \(u_{*}\), that can be used to derive wind and turbulence profiles. It is assumed that, regardless of the underlying surface, the wind speed at the top of the boundary layer (at a height of 500–1000 m) is approximately equal to the equilibrium wind speed defined by the geostrophic wind speed, which is based on the synoptic pressure gradient. The wind-speed profile conforms to Monin–Obukhov similarity theory, with friction velocity \(u_{*}\) as the key scaling velocity, and two additional scaling lengths, the surface roughness length \((z_0)\) and the surface displacement length \((d)\). For neutral or adiabatic conditions the wind-speed profile can be described by

\[
U = \frac{u_{*}}{k} \ln \left( \frac{z}{z_0} \right)
\] (2)

where \(k\) is the von Karman’s constant taken to be 0.4. Estimates of the surface roughness length \((z_0)\) and the displacement length \((d)\) can be made using information about urban morphology; building sizes and spacing (Macdonald et al., 2000). Due to the fact that urban areas have different frontal area densities \((\lambda_f)\), different flows can be observed which are also affected by the building area density (Grimmond and Oke, 1999 and Ratti et al., 2002). Despite the fact that the flow velocity follows a logarithmic profile, it is unclear how it behaves in the roughness sublayer (Britten and Hanna, 2003). The flow in the roughness sublayer encounters obstacles of different shapes and heights which complicate further the flow below the urban canopy (below the average building height). A simplified in-canopy velocity scale \((U_c)\) was deduced by Bentham and Britter (2003) by considering a constant velocity within the canopy layer instead of the usual logarithmic profile. Results for the in-canopy velocity scale, \(U_c\), were compared to a number of experimental wind tunnel data and were found in good agreement. In addition to the model for the in-canopy velocity scale, \(U_c\), another model was derived for the exchange rate; the rate at which the emissions are lost from or added at the top of the canopy. The exchange velocity \((U_e)\) result could not however be validated directly with experimental data but it shows the correct variation of \(U_e\) and predicts exchange rates similar to street canyon experiments (e.g. Caton et al., 2003). Introducing more buildings in the domain should facilitate more exchange due to the production of turbulence and should increase up to the point where skimming flow will start when the two velocities \(U_e\) and \(U_{ref}\) are no longer related.

Hamlyn and Britter (2005) applied the concept model for the exchange velocity as a ratio of the momentum flux to the difference between the mass flux above and below the canopy top (exchange plane).

\[
U_e = \int \left( \frac{\rho u w + \rho w u}{\rho u_c} \right) ds
\] (3)

The momentum flux in Eq. (3) is evaluated from the Reynolds’ shear stresses and the average values of the x and z components of velocities. Results showed that the exchange velocity \(U_e\) was around 1% of a reference wind speed at a height of 2.5H for the arrays with packing densities of \(\lambda = 0.0625\) and \(\lambda = 0.16\). For the denser array \((\lambda = 0.44)\) the exchange velocity is 0.3% of \(U_{ref}\) where skimming flow was starting to be present at high packing densities (Hamlyn and Britter, 2005).

Building on the work by Hamlyn and Britter (2005), the aim of the present study is to investigate the concept of the exchange velocity, as a measure of city breathability, within a real inhomogeneous urban area at the neighbourhood scale and deduce its spatial variability in such inhomogeneously varying geometries; furthermore it aims to examine the connection of the exchange velocity with the local urban geometry parameters. Through a novel way of examining the mean features of urban flow in real inhomogeneous geometries, this work derives the city breathability as a novel dynamic urban design characteristic relating to the city ventilation capacity. Moreover, this work examines the spatial variation of such a ventilation capacity within a real city and its relation to local and global urban geometrical properties and thereby the implications for operational model development. Due to the use of real geometry, the results of this work may shed light to urban designers as to how results from existing idealised studies on the impact of various geometrical urban features on city breathability may vary when considering real inhomogeneous urban geometries.

The paper has the following structure: Section 1 introduces the scope of the present study and reviews recent relevant literature while the methodology followed in the study is analysed in Section 2. Section 3 contains the results of the study along with analysis and discussion and finally conclusions are drawn in Section 4 with possible future work suggestions.

2. Methodology

2.1. The geometry and the numerical model

The urban area under investigation centers on the intersection of Marylebone Road and Gloucester Place in Central London, UK and spans an area of 250 m-radius. Marylebone Road is a busy dual carriageway, in places up to 7 lanes. From topographical maps of the area, the average building height of the area is estimated to 22 m and from the specific building arrangement the urban morphometry parameters are estimated as \(\lambda_f -0.25\) and \(\lambda_p -0.5\). In the CFD simulation, a 1:200 scale model of the urban area is represented and the resolved built area includes 42 buildings, with an average model building height of \(H_{m}\) of 0.11 m. The resolved built area and the area of interest are depicted in Fig. 1a (Google Earth, 2010).

The flow simulation is produced by solving the 3-D Navier–Stokes equations coupled with a seven-equation Reynolds–Stress turbulence model (RSM) (Lauder et al., 1975), implemented in the CFD code FLUENT (FLUENT, 2003). RSM provides the necessary functionality and allows for anisotropic turbulence (which is known to be a characteristic feature behind bluff obstacles), despite its inherent complexity and a tendency to overestimate the wake region behind a single cube obstacle (Murakami, 1998). On the other hand, the k-ε family of turbulence models imposes isotropic modelling of turbulence, a state that cannot necessarily be set as representative of the turbulence in a highly variable, spatially-inhomogeneous urban environment. Moreover RSM
has been compared with experimental results and time-averaged LES results for an urban like flow and has shown satisfactory agreement (Hamlyn, 2006). Steady simulations were carried out giving a time-averaged view of the flow, neglecting possible phenomena such as unsteady vortex shedding and occasional sweeps of air from above the canopy (Finnigan, 2000). This work focuses on novel ways of examining the mean features of the flow in a real city neighbourhood geometry and its associated ventilation capacity as well as the implications that arise for urban designers and planners when considering some existing idealised studies. The context of this model application is to address the steady state of the flow and achieve fit-for-purpose accuracy for the above aims. Validation of the employed CFD code against specific modelling objectives and data sets was performed through the EU COST action 732, which as result, a set of guidelines was deduced to ensure best practice of the code (COST Action 732, 2007). These guidelines were followed in this work to ensure best-practice of the CFD code.

The modelled neighbourhood area is illustrated in Fig. 1; the computational domain however extends a further distance both in the upstream and downstream directions of the outermost features of the built-area model, according to published numerical simulation design recommendations (Cowan et al., 1997 and COST Action 732, 2007). The domain size is 6.2 m (x-direction) by 3 m (y-direction) by 0.55 m (z-direction) corresponding to $56H_m \times 27H_m \times 5H_m$. The geometry was prepared using the pre-processor GAMBIT (FLUENT, 2003).

The grid size of the modelled domain is close to 4 million cells. The mesh was distributed densely around the building faces. Grid size around the building is on average 0.025 m which corresponds to 23% of the average building height. A mesh sensitivity analysis was carried out to prove the independence of the numerical results to the grid size. A coarser mesh of around 1.6 million cells with grid size of 30% and a finer mesh of around 8 million cells with grid size of 12.5% were simulated to the acceptable convergence criteria for the residual errors (as per COST732 guidelines). Vertical velocity profiles resulting from all three different mesh simulations were compared for canyons both in parallel to the flow (Marylebone Road) and vertical (Gloucester Place). The three mesh simulations showed velocity profiles with the coarser mesh overestimating the lower height numerical values, with the other two meshes having similar profiles with differences ranging from 2.5% to 10% depending on the depicted location.

In our computational domain an inflow condition was applied at the leftmost (upwind) boundary (y–z plane) of the domain (Fig. 1b). An inlet wind profile is specified according to Eq. (2) and the values of the surface roughness and displacement lengths were calculated from the referenced literature. For the turbulence parameters, profiles of
the turbulent kinetic energy and the turbulent dissipation rate were specified according to design rules (Richards and Hoxey, 1993). The value for the surface roughness length \( z_0 \) was taken as 0.0014 m from wind tunnel experiments and a value of 1.14 m was used for the displacement length \( d \) (Macdonald et al., 2000). A pressure outlet condition was applied at the rightmost (downwind) side (y-z plane) of the domain. Symmetry boundary conditions (zero mean flow and zero normal gradient of all quantities at the plane) were applied at the northern and southern sides (x-z planes) of the domain (y-direction pointing to the north in Fig. 1). A symmetry condition was also applied at the horizontal top of the domain (x-y plane) and the wall boundary condition (with standard wall functions) was applied at the ground and building surfaces. The solver settings were set with discretisation scheme of second-order upwind for momentum, SIMPLE pressure-velocity coupling as well as first order upwind scheme for turbulent kinetic energy and turbulence dissipation energy.

2.2. Post-processing methodology

The urban area on which the post-processing study concentrated was an area in the middle of the domain around the road junction of Marylebone Rd and Gloucester Rd (Fig. 1) where the flow is well developed in the in-canopy region without being affected by the flow at the ends of the domain. In a more detailed examination of the geometry it was decided to use an even smaller control volume module for the deduction of the exchange velocity. It is important to note that in an idealised geometry, as for example in the case of a regular array of cubic obstacles with the rows being perpendicular to the wind direction (e.g. as in Hamlyn and Britter, 2005) the control volumes are defined by dividing the regular array of cubic obstacles into repeating units consisting of one cube with half canyons at both ends and half side channel. In the same rationale, in our inhomogeneous geometry, a control volume of consecutive buildings with similar heights was chosen. One such set of buildings was identified and is shown in Fig. 2 along with the control volume around building 1b with the exchange plane at the top of the building. The choice of this specific control volume avoids ambiguity in defining the exact shape of the control volume in the case of an uneven canyon.

The air flow exchange between the in-canopy and above-canopy flows is directly linked to the momentum fluxes across the canopy top; Reynolds’ stresses which are the turbulent component of this momentum flux across the top are considered to be the dominant mechanism of exchange, with the mean component to be negligible compared to the turbulent one. Therefore Reynolds’ stresses become the key feature in this flow exchange and the characterisation of the “breathability” of the urban canopy. For the scope of this paper, it can be noted that the overall variations of turbulence kinetic energy and turbulent dissipation rate are consistent with known features of flows behind bluff bodies. In the exchange velocity computation as described in Eq. (3), the canopy-top momentum flux may be written as the sum of the rooftop level surface integrals of the flux due to turbulence (Reynolds’ stresses), since turbulence is the dominant mechanism of exchange.

The variable \( A_C \) in Eq. (3) is the cross sectional area of the exchange plane and \( U_{ref} \) is the average velocity of the flow at a height of \( 2.5H \), where \( H \) is the height of the specific building in the control volume. The reference height, for which the above-canopy velocity is calculated, must be chosen so that it is sufficiently above the rooftops and hence the flow is well developed. A validation work was carried out using vertical profiles of the \( u \)-velocity to prove the developed nature of the flow at 2.5\( H \) and whether it is appropriate to use this as the reference height.

The in-canopy velocity scale, \( U_c \) can be determined by the pressure force exerted on the obstacle and the drag coefficient \( C_D \) by postulating in Eq. (4) below that:

\[
U_c = \sqrt{\frac{2F_p}{\rho C_D A_f}}
\]

where \( C_D \) is the drag coefficient, \( A_f \) is the frontal area of the obstacle, \( \rho \) is the air density, and \( F_p \) is the pressure force exerted on the obstacle and is evaluated by the net pressure surface integral on the frontal and back area of the obstacle. The in-canopy velocity scale is not constant throughout the domain and it changes from building to building; as a result it is more appropriate to use a specific in-canopy velocity scale for each control volume. There is no reported value for \( C_D \) in the literature for a cubical obstacle located amongst a large group of obstacles, and therefore a standard value (of 1) was chosen for \( C_D \) to avoid any bias arising from any other undocumented choice. According to Macdonald et al. (1998) the drag coefficient for a building in an area with changing flow velocity is related to the drag coefficient of the obstacle in a free stream flow according to \( C_{D_{HI}} = (u_{\infty}/u_{HI})^2 C_{D_{\infty}} \). The velocity at height \( H \) is not however related to the free stream velocity and a method has to be devised to evaluate this variable as well as the drag coefficient of the unobstructed building. Moreover, in this investigated

![Fig. 2. Example of control volume and reference planes (buildings 1a and 1b).](image-url)
case, an additional modification should be made in order to account for the presence of other obstacles surrounding the building/bluff body (compared to what is currently documented in the literature, i.e. a bluff body isolation). In order to avoid ambiguous use of modifications, we postulate an in-canopy velocity scale \(U_C\) (instead of an absolute in-canopy velocity).

The exchange velocity \(U_C\) was first deduced from a control volume defined around building 1b. The same method of evaluating \(U_C\) using the reference velocity at a height of 2.5 of each building's height (i.e. 2.5\(H\)), was employed for a total of 14 buildings as identified in Fig. 1. Because of the inhomogeneity of the urban geometry, it is important to clearly define the inlet and outlet planes as well as the criteria for the reference variables for each control volume. The different planes of interest for the required variables are illustrated in Fig. 2 for the building 1b as an example. The reference plane is shown in grey and at a height 2.5 times the height of each building. The exchange planes where the exchange processes take place are shown as a horizontal surface in white around the rooftop (canopy-top) of each building and the walls are displayed as vertical surfaces also in white at which the pressures before and after each building are to be evaluated.

3. Results and discussion

In order to have an overview of the flow field resulting from the simulation and its physical form and complexity, visualisations of the flow field within the modelled urban area were made using tracking features produced with massless tracer particles. Such tracer particles were released from selected building surfaces of interest in order to illustrate schematically salient flow features. It has to be noted that these visualisations do not analyse the vortical structures but rather provide a qualitative view of the flow structures and their complexities. It is also important to note that in reality such vortical structures have an unsteady nature and the simulation of their very precise form may vary depending on the models used.

Figs. 3 and 4 show the velocity contours in plan views (horizontal planes) and at vertical cross-section, while Fig. 5 depicts the visualisations obtained from particle path lines by releasing tracer particles from the sides and rooftops of a number of buildings in the domain. The visualisations show that the flow is dominated by large vortical structures whose form varies with the particular building obstacle area. These vortical structures mix air from the top of the urban canopy with air within the canopy and vice-versa. Some vortical structures also seem to mix air across the width of canopy but across smaller distances. The vortex patterns appear to originate in the short canyons behind buildings and are different from the archetypal 2-D street canyon flows. It is noted that the formations observed here are time-averaged simulated results. Similar patterns have also been observed in corresponding steady simulations of regular cube arrays (Hamlyn and Britter, 2005). This visualisation suggests that the form of these vortices may influence the effectiveness of vertical mixing (and air replenishing) within the canopy. Thus the concept of an exchange velocity, as defined by the average velocity of transfer of mass into or out of the canopy can be used. This exchange velocity would be directly relevant to the removal of polluted air and heat from urban canopies.

The flow was further examined in the regions closer to the canyons and around the buildings by the release of massless tracer particles. Particle path lines are released from the sides and rooftops of a number of buildings in the domain. The visualisations are shown in Fig. 5 from which the nature of the vortices in the canopy can be identified. At the south side of the canyon, the flow separated off the side wall and forms a vertical vortex. Towards the lateral centre of the canyon the vortex is clearly seen to shift into a horizontal axis with flow coming from the roof separation. The two buildings in the investigation are very similar with a packing density of approximately 0.4–0.5. These visualisations are consistent with the results of Hamlyn and Britter, 2005 for their model with packing density 0.44 where it was observed that the flow consists of a single vortex that is primarily driven from the separation off the sides; at first it has a vertical axis which then bends over to the horizontal closer to the lateral centre. For lower packing densities, according to the work of Hamlyn and Britter (2005) on idealised cubical arrays, two vortical structures are generally observed for their model with packing density, \(\lambda_p = 0.16\). The side vortex is a recirculation of the flow behind the obstacles due to the flow separation off the side faces and it has a vertical axis. The second vortex, referred to as main vortex, is created due to the separation off the top of the building and it has a horizontal axis. It is more dominant near the lateral centre since towards the side ends it interacts with the side vortex. Further downstream in the canyon the flow is dominated by the main vortex from the top.

In our visualisations in the inhomogeneous urban geometry, helical vortices are observed through the canyons. The flow appears confined (or trapped) within the canyons; this kind of trapped, swirling air masses help the dilution in the canyon but not the ventilation directly through the canyon top interface with the atmosphere above. Investigating further the air flow and the vertical structures within the canyons, velocity profiles were plotted for vertical lines along the canyon in the central part of the canyon. The velocity (Fig. 6) near the main road has a large positive value and as the flow moves into the canyon, it acquires negative values and again changes back to positive which confirms the presence of swirling vortices in the side canyons. These characteristics of the flow field, dominated by vortical structures, will aid the diffusion of pollutant released from the street level as well as the mixing of air from above and below the canopy. The concept of an exchange velocity, presented in Section 2, was used to evaluate the “breathability” of the domain. By
taking results from many building sets the appropriateness of the exchange velocity concept on a realistic complex geometry was investigated.

3.1. Velocity field

A strong flow channelling along large roads (e.g. Marylebone and the outermost parallels) is observed. Strong preferential channelling is also observed in the perpendicular direction to the original approaching wind flow direction e.g., in the case of Gloucester Road from south to north direction; however, cross-wind channelling appears less strong than the wind-wise direction.

Fig. 3 depicts the contours of wind speed on three different horizontal surfaces, at heights $z = H/2$, $H$, and $2H$. The colourbar is clipped to the global maximum and minimum values of velocity. A key flow feature is the presence of wakes formed as the air flows over and around building obstacles. As we move closer to the ground, more buildings are present inside the wakes of neighbouring buildings. Another flow feature observed is the presence of shear layers, e.g. very close to the edge of

![Fig. 4. Velocity contours of the flow field on a vertical surface slice at $y = -0.45H_{\text{nr}}$.](image)

![Fig. 5. Visualisation by release of massless particles from side walls and/or roof surfaces of the upstream building of the canyon in reference: (i - top image) Vortices formed with horizontal axis in the downstream region of building 1a, (ii - middle image) Vortices formed with horizontal axis in the downstream region of building 3b (side view - flow from left to right), (iii - bottom image) Path lines generated by releasing particles on the sides of buildings both at the north and south of Marylebone Road showing vortex generated with vertical axis behind the side of the buildings (top view - flow from left to right).](image)

![Fig. 6. (a) The location of the vertical-profile lines depicted in the centre of the canyon between buildings 1a and 1b. (b) Vertical profiles of the horizontal velocity $u$ at the locations depicted in Fig. 6a.](image)
the wedge-like building in the contour plot at \( z = H \); overall, higher velocities are also seen throughout the domain compared to the velocity field observed at lower vertical heights. In the contour plot at height \( z = 2H \), only the highest buildings (the three towers) are met by the air flow; the wakes of these buildings are the main disturbances to a bulk flow of seemingly higher velocities than those observed at lower heights.

In Fig. 4 the contours of wind velocity on a vertical cross-section at mid-span of the domain (i.e. at \( y = -0.5m \)) are presented. The incoming flow is in the direction from left to right, and the colourbar is clipped to the maximum and minimum values. The speed contour plot shows how air movement within a street canyon is more, or less, enhanced, depending on the upwind buildings but sometimes on the downwind buildings as well. In the last downwind canyon for example depicted in the figure, air movement is induced from a small recirculating region formed by the main wind flow facing the tower (last building) just downwind the canyon.

The main variable to be used in the analysis and explanation of the flow is the \( u \)-velocity. The inlet velocity profile is a logarithmic profile with Eq. (2) \( U = \frac{k}{\mu} \log(z/z_0) \) and develops to 3 m/s. This profile changes substantially when the flow interacts with the buildings and marks a substantial qualitative difference between the velocity field within the canopy and that above the canopy and denotes the shear that the buildings exert on the flow above. Post-processing of the numerical data can lead to a deduction of this shear which can be related to a corresponding exchange velocity (like an entrainment velocity) based on its definition in Eq. (3). The velocity profiles in and above the canopy are simplified to constant velocities with \( U_c \) being the in-canopy and \( U_{\text{ref}} \) the above canopy velocity using a reference at a height \( z_c = 2.5H_{\text{ref}} \) also used by Bentham and Britter (2003). For this study involving a complex inhomogeneous urban canopy with uneven building heights, a rigorous definition of the reference height must be used. Defining different vertical levels along the domain and specifically over each of the buildings within the area of interest, velocity profile plots were created for each building in an attempt to evaluate the velocity at 2.5H and look into the appropriateness of using 2.5H as the reference height as depicted in Fig. 2.

Summarising the plots with data for a number of consecutive buildings in the domain in Fig. 7, it can be seen that the pattern of velocity profiles does not vary substantially from one building to the next with only a few exceptions; below the rooftop level the wind velocity decreases through an inversion/recirculation towards zero velocity, whereas above the rooftop level the wind velocity monotonically increases in a logarithmic-like fashion. In the exemption cases where there is a tall building downwind the building under consideration (e.g. for building 8, the Tower-Building 1 is just downwind), the wind velocity above the rooftop level does not increase monotonically but forms a wake-like velocity profile. This is important since it was expected that dissimilar variations in the profiles would appear due to the inhomogeneity of the domain - primarily due to the height variations. Comparing further with the building height of each building it can be said that the flow is somehow developed at a height of 2.5H and hence this can support the choice as the reference height for each building at which the velocity reference will be evaluated.

Furthermore Fig. 7 also supports the conceptual model that two characteristic average velocities may be taken for the flow through an urban canopy: a slower velocity within the canopy and a faster one, closer to the bulk velocity over the average building height. This large difference in wind flow velocities acts as a shear inducing a driving mechanism for the exchange flow between in- and above-canopy flows and thereby the city ventilation or breathability.

### 3.2. Exchange velocity

Exchange velocity results were represented in a normalised form \( U_d/U_{\text{ref}} \), namely as a velocity exchange coefficient, also used in the works of Hamlyn and Britter (2005) and Bentham and Britter (2003). In Bentham and Britter (2003) the total floor area is used as the area of exchange whereas the equation model of Hamlyn and Britter (2005) uses the true area of exchange at the canopy top. In an effort to make the two sets of results comparable, the predictions of the first were adjusted by a factor of \((1 - \lambda_p)\). The deduced numerical values for the \( U_d/U_{\text{ref}} \) coefficient for building 1b are first analysed since this specific building-control volume can be considered similar to the regular cube arrays of the aforementioned works. Results for building 1b show that the exchange velocity is approximately 1.4% of the reference velocity which is comparable to the results of \( U_d/U_{\text{ref}} \% \) reported by Hamlyn and Britter (2005). The momentum flux is assessed at a vertical height equal to the building height, \( H \), while the reference velocity was taken at a height of 2.5H.

The exchange velocity coefficient was derived for all the buildings by defining an appropriate control volume for each building; the results for all buildings – are listed in Table 1. Specifically the derived exchange velocity coefficient is shown for the corresponding local packing density that each building with its associated surrounding canyon width corresponds to. The locally defined packing densities ranged in the entire domain from 0.04 to 0.07. For most cases the deduced values of the exchange velocity coefficients range between 0.01 and 0.03 while for a couple of buildings it ranges around 0.04–0.06 and 0.13. The results compare favourably to those reported by Hamlyn and Britter (2005) with some slightly increased values for the corresponding \( \lambda_p \); this is not surprising as considering the inhomogeneous urban geometry and the associated increased turbulence and resulting mixing, it is expected to yield some higher values of \( U_d/U_{\text{ref}} \).

The three buildings (4a, 4b, 8) that appear to give inconsistent results with the rest of the presented results are all three located near the edges of the domain (second row) having exposed walls on the incoming air flow causing a much higher pressure difference and hence higher values of the in-canopy velocity. This in turn gives rise to a very small difference between the in-canopy and reference velocities due to the pressure force which is around an order of magnitude greater than that found on other buildings and hence the exchange velocity is larger. For example the exchange velocity of building 4b is about two orders of magnitude higher than the rest of the buildings and the corresponding values for buildings 4a and 8 are found to be one order of magnitude higher.

The vertical profile of the horizontal \( u \)-velocity (in x-direction) on building 9 suggests that there is an enhanced flow compared to the upstream flow; specifically the flow is enhanced by a stream of lateral flow in the canyon upstream of building 9, and because of this flow the profile does not develop at the reference height of 2.5H and hence \( U_{\text{ref}} \) is lower than the in-canopy one. As a result the exchange velocity is an order of magnitude higher than the values in the rest of the cases. For building 7, the vertical profile of the horizontal \( u \)-velocity (in x-direction) suggests that there is an abnormal flow over the building; this is caused by the complexity of the building geometry itself which is a two-structure building as shown in Fig. 1: a U-shaped building of height 0.084 m (corresponding to 0.76\( H_{\text{ref}} \)) also taken as the canopy top height) and the inside structure of a height of 0.120 m (corresponding to 1.1\( H_{\text{ref}} \)). It was seen that the reference height of 2.5H was inappropriate due to the undeveloped flow caused by the taller inner building. However values of \( U_d/U_{\text{ref}} \) near 0.05 are considered acceptable; taking the reference height at a higher plane for a more stable \( U_{\text{ref}} \) closer to the free stream, brings the ratio of \( U_d/U_{\text{ref}} \) closer to 0.01.

The work by Hamlyn and Britter (2005) in idealised cubical arrays shows the exchange velocity decreasing as the density of the array increases; this is due to the onset of skimming flow over the regular array. In our study of an inhomogeneous urban area, the local packing densities \( \lambda_p \) (defined for each building with its surrounding half space range between 0.36 and 0.68) (Fig. 8) are consistent with the more global packing density of 0.55 as reported by Ratti et al. (2002) for the city of London. Plots of \( U_d/U_{\text{ref}} \) coefficients against the corresponding local \( \lambda_p \) show a trend where the exchange velocity increases for \( \lambda_p \) between 0.3 and 0.5 and then starts to decrease. Packing densities of 0.6 and above exhibit the lowest values of exchange velocities due to
the skimming flow pattern. This proves that skimming flow on densities of 0.5–0.55 and above prevents the air to penetrate inside the canyon and hence the exchange velocity and the city breathability are decreased. Results by Solazzo and Britter (2007) show that the value for the exchange velocity $U_E$ over a single canyon is approximately around 1% of their reference velocity that is taken to be the inlet domain velocity. In a later study by Chan et al. (2003) a RANS simulation on 2D street canyon flows was carried out while the property of the air exchange rate (ACH) was firstly introduced by Liu et al. (2005). The results of this study are comparable with the ACH of Liu et al. (2005) with acceptable deviation (Fig. 8). The results of $U_E/U_{ref}$ illustrated in Fig. 8 show that is possible that a pattern can be derived with regard to the effect of the building packing density on the air flow exchange and thereby the breathability capacity of a city. We observe that in both homogeneous and inhomogeneous cases, the highest normalised exchange velocity is observed in the middle range of building packing densities $\lambda_p$, i.e. in the wake interference flow regimes. The observed exchange velocities in the inhomogeneous geometries are overall higher than those in homogeneous urban geometries (Table 2).

### 3.3. Exchange velocity ($U_E$) and turbulent kinetic energy (TKE)

Variations of exchange velocity $U_E$ with respect to the turbulent kinetic energy TKE$_r$ are plotted in Fig. 9 in order to compare the

<table>
<thead>
<tr>
<th>$\lambda_p$</th>
<th>$U_E/U_{ref}$ at 2.5H (local)</th>
<th>$U_E/U_{ref}$ at 2.5Hm (global)</th>
<th>$\lambda_p A_{roof}/A_C$</th>
</tr>
</thead>
<tbody>
<tr>
<td>bld 1</td>
<td>0.0045</td>
<td>0.0040</td>
<td>0.68</td>
</tr>
<tr>
<td>bld 1a</td>
<td>0.0648</td>
<td>0.2363</td>
<td>0.55</td>
</tr>
<tr>
<td>bld 1b</td>
<td>0.0141</td>
<td>0.0204</td>
<td>0.53</td>
</tr>
<tr>
<td>bld 2a</td>
<td>0.0266</td>
<td>0.0359</td>
<td>0.64</td>
</tr>
<tr>
<td>bld 2b</td>
<td>0.0205</td>
<td>0.0305</td>
<td>0.66</td>
</tr>
<tr>
<td>bld 3a</td>
<td>0.0145</td>
<td>0.0161</td>
<td>0.36</td>
</tr>
<tr>
<td>bld 3b</td>
<td>0.0474</td>
<td>0.0450</td>
<td>0.39</td>
</tr>
<tr>
<td>bld 4a</td>
<td>0.1312</td>
<td>0.1436</td>
<td>0.45</td>
</tr>
<tr>
<td>bld 4b</td>
<td>0.9679</td>
<td>0.4833</td>
<td>0.51</td>
</tr>
<tr>
<td>bld 4c</td>
<td>0.0360</td>
<td>0.0213</td>
<td>0.58</td>
</tr>
<tr>
<td>bld 6</td>
<td>0.0264</td>
<td>0.0306</td>
<td>0.46</td>
</tr>
<tr>
<td>bld 7</td>
<td>0.0499</td>
<td>0.0324</td>
<td>0.54</td>
</tr>
<tr>
<td>bld 8</td>
<td>0.1297</td>
<td>0.1039</td>
<td>0.51</td>
</tr>
<tr>
<td>bld 9</td>
<td>0.5648</td>
<td>0.7047</td>
<td>0.41</td>
</tr>
</tbody>
</table>

Fig. 7. Line plots of successive buildings 8, 1, 1a, 1b as indicated in Fig. 1 along the direction of the flow.
correlation of the two quantities. The resulting plot suggests that there is no direct relation between the two quantities in this over a the complex geometry and a pattern of how and why the two quantities vary may not be clearly established. Large exchange velocity values exist at buildings both at the beginning and at the end of the area under investigation as well as both north and south of Marylebone Road. As explained above, it was chosen not to work on the buildings near the domain edges due to the possible effect that the side flow may have on the exchange velocities and because the study is concentrated on the flow interaction with a complex urban area. Considering the fact that the domain is inhomogeneous and that no specified framework is set for the determination of referencing in such a complex realistic domain, the above results for the 14 buildings with most values of $U_E/U_{ref}$ ranging from ~0.005 to 0.07 are of the same order of magnitude and similar to Hamlyn and Britter’s (2005) results of 0.0032 for packing density $\lambda_p$ of 0.44 as well as Bentham and Britter’s (2003) adjusted values of 0.038 (Fig. 8). These results prove that the thought of increased exchange velocity in the complex geometry is valid and results from the increased mixing between above and below canopy air. A further investigation was carried out to assess the validity of the reference velocity. $U_{ref}$ was initially taken at a height of 2.5H for each building (locally) and then evaluated at a height of 2.5 times the average building height, $H_m$ (global). It can be seen through Fig. 8 that the ratio $U_E/U_{ref}$ for the majority of the buildings is similar to both methods of velocity referencing. This proves that both methods of referencing are acceptable and give similar results. In addition an average value of $U_{ref}$ at 2.5$H_m$ was used for all buildings and showed results with small deviations for the buildings with $U_E/U_{ref}$ below 0.05. The inlet velocity, $U_{in}$ was also used as another option for referencing the velocity above the canopy; it was observed that the trends of the results were similar. Such results could be proven useful in operational field experiments with large sampling numbers of buildings where it is difficult to use a local referencing while a more global referencing could be more operationally useful. However they provide acceptable results with less computation time which would probably be applicable to operational models.

A critical difference of this work addressing a complex inhomogeneous geometry compared to the regular cube-array studies is the arising inhomogeneity of the flow around each building. In the regular cube arrays the flow profile develops over a number of building rows and hence consistent results can be reached. In the complex domain however, wakes from upstream buildings create vortical structures which in turn become the incoming flow on the next downstream building with irregular structure and direction. The $u$-velocity component does change rapidly and unexpectedly from building to building thus leading to inhomogeneous results.

### 4. Conclusions

The wind flow through a realistic complex urban geometry and the flow exchange processes developed within were examined using numerical results from a CFD simulation. The CFD simulation was performed by solving the steady Navier–Stokes equations using the RSM turbulence model with a high resolution mesh. Initially the flow was qualitatively assessed using flow visualisations where large vortical structures were identified whose shape and size varied according to the particular building area. Compared with the visualisations of regular cube arrays (by Hamlyn and Britter, 2005) the vortices which are created in the canyons of the inhomogeneous urban geometry have some basic similar characteristics with those in the idealised geometries, i.e. starting initially as horseshoe-like vortices with vertical axis due to the separation off the building sides and then shifting into ones with horizontal axis after they combine with the flow separating off the rooftops. However due to the complexity of real urban geometry, enhanced mixing is evident due to the channelling flow in the main streets and the vortical structures that develop and merge from within different streets and canyons.

### Table 2

<table>
<thead>
<tr>
<th>$U_E$</th>
<th>$KE_{urb}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>bld 1</td>
<td>0.0002</td>
</tr>
<tr>
<td>bld 1a</td>
<td>0.335</td>
</tr>
<tr>
<td>bld 1b</td>
<td>0.0017</td>
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<tr>
<td>bld 2a</td>
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</tr>
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<tr>
<td>bld 4b</td>
<td>12.1208</td>
</tr>
<tr>
<td>bld 4c</td>
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</tr>
<tr>
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<td>0.1653</td>
</tr>
<tr>
<td>bld 9</td>
<td>1.9171</td>
</tr>
</tbody>
</table>

Fig. 8. Plot of the exchange velocity coefficients $U_E/U_{ref}$ against the packing density $p$ in different studies and for different definitions of $U_{ref}$.
The concept of exchange velocity was investigated and numerical values of the exchange velocity were deduced from the CFD simulations. Exchange velocities were deduced by defining appropriate control volumes around each individual building and considering buildings centrally in the domain and neglecting buildings near the domain edges in order to avoid any domain-edge effects on the flow. The results show that the normalised exchange velocity (exchange to reference velocity ratio/coef, $U_e/U_{ref}$), ranges from 0.005 to 0.13 for a local packing density, $\lambda_p$, ranging from 0.4 to 0.7 in a real urban geometry. These results are found to be consistent with those from regular cube arrays (e.g. by Hamlyn and Britter (2005) and Bentham and Britter (2003)). From the results of $U_e/U_{ref}$ (Fig. 8) a pattern can be derived for the effect of packing density of the buildings to the air flow exchange velocity and thereby to the breathability of a city. Results of $U_e/U_{ref}$ against the corresponding $\lambda_p$ show a trend where $U_e$ increases for values of $\lambda_p$ between 0.3 and 0.5. Exchange velocity then starts to decrease with lowest values beyond packing densities of 0.6. This proves that the initiation of skimming flows, on densities of 0.55 and above, prevents the air to penetrate inside the canyon and hence decreases the exchange velocity and the city breathability. We observe that inhomogeneous geometries likewise to homogeneous ones exhibit the highest normalised exchange velocity in the middle range of building packing densities $\lambda_p$, i.e. in the wake interference flow regimes; however the observed exchange velocities in the inhomogeneous geometries are clearly higher than those in homogeneous urban geometries, often almost twice as much. This result may also provide a useful insight for urban planners and designers interested in examining how reported results on city breathability variation with packing density from idealised studies may alter when investigating a real urban neighbourhood, in the context of its local breathability variation with respect to the local packing density of the urban geometry.

Reference velocity was taken at a vertical height of 2.5 times the building height ($H$) following the investigation of the $u$-velocity vertical profile over buildings in the area of interest. Investigation on the importance of reference velocity and how it affects the evaluation of the exchange velocity coefficient was also carried out, proving that for those buildings with ratios $U_e/U_{ref}$ less than 0.05 are negligibly affected by the small differences in the reference velocities whereas the ones that have ratios up to 0.15 show a small influence ($-0.10$) for the specific range of reference velocities. This supports that referencing at 2.5 $H$ (local building height) and at 2.5 $H_{avg}$ (global average building height), as well as $U_{ref}$ give comparable results, thus allowing computations to be carried out with global average height values used and for comparing the results with experimental studies in which referencing is done on a global broader area.

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