Air flow and pollution in a real, heterogeneous urban street canyon: a field and laboratory study

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Abstract

In this work we investigate the influence of real world conditions, including heterogeneity and natural variability of background wind, on the air flow and pollutant concentrations in a heterogeneous urban street canyon using both a series of field measurements and controlled laboratory experiments. Field measurements of wind velocities and Carbon Monoxide (CO) concentrations were taken under field conditions in a heterogeneous street in a city centre at several cross-sections along the length of the street (each cross-section being of different aspect ratio). The real field background wind was in fact observed to be highly variable and thus different Intensive Observation Periods (IOPs) represented by a different mean wind velocity and different wind variability were defined. Observed pollution concentrations reveal high sensitivity to local parameters: there is a bias towards the side closer to the traffic lane; higher concentrations are found in the centre of the street as compared to cross-sections closer to the junctions; higher concentrations are found at 1.5 height from the ground than at 2.5 m height, all of which are of concern regarding pedestrian exposure to traffic-related pollution. A physical model of the same street was produced for the purpose of laboratory experiments, making some geometrical simplifications of complex volumes and extrusions. The physical model was tested in an Atmospheric Boundary Layer water channel, using simultaneously Particle Image Velocimetry (PIV) and Planar Laser Induced Fluorescence (PLIF), for flow visualisation as well as for quantitative measurement of concentrations and flow velocities. The wind field conditions were represented by a steady mean approach velocity in the laboratory simulation (essentially representing periods of near-zero wind variability). The laboratory investigations showed a clear sensitivity of the resulting flow field to the local geometry and substantial three-dimensional flow patterns were observed throughout the modelled street. The real-field observations and the laboratory measurements were compared. Overall, we found that lower variability in the background wind does not necessarily ensure a better agreement between the airflow velocity measured in the field and in the lab. In fact, it was observed that in certain cross sections, the airflow was more affected by the particular complex architectural features such as building extrusions and balconies, which were not represented in the simplified physical model tested in the laboratory, than by the real wind field variability. For wind speed comparisons the most favourable agreement (36.6% of the compared values were within a factor of 2) was found in the case of lowest wind variability and in the section with the most simple geometry where the physical lab model was most similar to the real street. For wind direction comparisons the most favourable agreement (45.5% of the compared values was within $\pm 45^{o}$) was found in the case with higher wind variability but in the cross-sections with more homogeneous geometrical features. Street canyons are often simplified in research and are often modelled as homogenous symmetrical canyons under steady flow, for practical purposes; our study as a whole demonstrates that natural variability and heterogeneity play a large role in how pollution disperses throughout the street, and therefore further detail in models is vital to understand real world conditions.

Keywords: field measurements, urban air pollution, PIV, PLIF, street canyon

1. Introduction

Urban air quality is primarily associated with the emissions produced by traffic and industry. The actual air ventilation within urban street canyons is of rising importance mainly due to its link to the pollutant removal capacity of specific street canyons and subsequently to the long-term air pollution exposure of citizens. Street canyons, where continuous buildings flank a street on both sides, are known to be the worst type of street design in terms of pollution dispersion, especially when the background wind is perpendicular to the street. There have been many laboratory and numerical studies, and fewer field studies, of air flow and dispersion in street canyons. The Height to Width (H/W) aspect ratio of the street was shown in numerous studies to be the main geometric parameter affecting street ventilation. One or more vortices might form in the street depending on this ratio and the direction of the above roof wind (Hunter et al., 1992; Sini et al., 1996). Neophytou et al (2014) determined the exchange velocity and hence the city breathability for street canyons of different aspect ratios. In all these studies, streets are assumed to be symmetrical and homogeneous and are simplified significantly both in physical models and in simulations; the resulting air flow patterns, including a persistent vortex formation in the street, are found to be very unfavourable for ventilation and pollution removal. Yet in a numerical study of an asymmetric canyon, Assimakopoulos et al. (2003) noted that in complex geometries, such as heterogeneous canyons, the flow field could significantly differ from the flow in a symmetrical, homogeneous street canyon

The formation of the street canyon vortex is also dependent on the stability of atmospheric conditions (Nakamura and Oke, 1988), and on ambient wind speeds being above 1.5 - 2ms^{-1} (DePaul and Sheih, 1986). Real world conditions were tested also by Qin and Kot (1993), Meroney et al. (1996), and Eliasson et al. (2006), who all found that under conditions of low background wind and weaker turbulence, vortices measured in the streets were less persistent. Klein and Clark (2007) found that a small variation in the wind above the roof produced an alteration in the flow properties in the street, and a vortex could not be identified under variable wind conditions. The variability of the wind above the roof also has a significant effect in the vicinity of intersections, where small changes can substantially shift the distribution of street flow angles (Balogun et al., 2010, Klein et al., 2007).

It is widely recognized that background meteorological conditions have an important impact on the dispersion of pollution within and above the city (e.g. Britter and Hanna, 2003; Li et al., 2009; Gu et al., 2011). However this relationship is not always clear. Reynolds (1996), reports that there was no linear relationship between concentration levels and background meteorological conditions. The effects of alterations in the wind flow patterns in the street considerably modify the local pattern of pollutant dispersion near the intersection or in the street. As a consequence of the variability in flow structure, it is estimated that measured concentration levels might differ from predictions (Mavroides et al., 2007). Schatzmann et al. (2000) carried out a field campaign in Hanover/Germany and showed that the concentrations reduced or increased depending on whether the background wind was perpendicular, oblique or parallel to the street canyon. In addition, Karra et al. (2011) showed that near the ground the concentrations are more affected by the location of the traffic lane than the meteorological conditions. Different measures to quantify the pollutant removal capacity have been proposed, such as the breathability (Neophytou and Britter 2005; Panagiotou et al. 2013; Neophytou et al. 2014) and mean age of air (Ramponi et al. 2015; Buccolieri et al. 2015). The concept of an “exchange” velocity has also been used in the literature, e.g. an air-exchange velocity which takes into account only the air-flow rate going in and out of a defined control volume (e.g. Bentham and Britter 2003; Li et al. 2005; Moonen et al. 2011; Panagiotou et al. 2013) or a pollutant-exchange velocity which takes into account also the distribution of pollutant concentration (Liu et al. 2005; Cheng et al. 2008, Kubilay et al, 2017).

Most of the street canyon studies reported above include comparisons between laboratory and simulations. Wind variability is largely acknowledged as an important factor in the differentiation of real field studies relative to laboratory studies or simulations under controlled conditions. However, there is only one reported study to our knowledge that compares a study under real field conditions with laboratory experiments: Blackman et al (2015), who studied the flow field inside an idealized (symmetrical and homogeneous) street canyon. Although they do not report any observations on the field wind variability, they found that overall agreement between lab and field results falls within 20%.

This paper addresses the issues that arise in "real" street canyons, of heterogeneity and of background wind variability, which are typically neglected in street canyon studies, to demonstrate that the situation in real streets is far more complex than expected. The real street conditions are fully investigated by drawing on a complementary set of information from both field measurements of airflow and dispersion inside a real heterogeneous canyon, and laboratory simulations of a reference case of steady, perpendicular flow in a physical model of the street, accounting for the large scale geometric complexity in the model. The field measurements of air flow and of traffic-related Carbon Monoxide concentrations were carried out in a typical Mediterranean heterogeneous street canyon in Nicosia, Cyprus, a tall narrow street with varying building shapes and heights. The laboratory experiments were carried out in a water channel, obtaining simultaneously the flow and concentrations through Particle Image Velocimetry (PIV) and Planar Laser Induced Fluorescence (PLIF) techniques, the simultaneous application of which has not been done for street canyon investigations to the best of our knowledge. The structure of the paper is as follows: Section 2 describes the methodologies for the field measurements and the experimental modelling, Section 3 presents observations of background wind, flow field and concentrations within the street for several wind cases, compares these qualitatively and quantitatively with the laboratory measurements, and discusses the effects of street geometry on the 3D flow field, and the effect of variable wind conditions. Finally, Section 4 presents Conclusions.

2. Methodology

2.1 Field Measurements

The field measurements were carried out in a typical Mediterranean heterogeneous street canyon in Nicosia, Cyprus, Rigenis Street, a tall narrow street with varying building shapes and heights. The street is shaded at that time of the day and upwards vertical velocities were not observed, thus buoyancy effects related to solar heating are not relevant. Rigenis Street is a one-way street with a South-East to North West orientation, is 160m long (L) and 8m wide (W) including the pavements, and has flat building roofs. The mean aspect ratio of the street is H/W=1.25. The South side of the street is 9.7m high on average with large variations in height up to a maximum of 11.5m. The North side is 9.9m high on average, has a mostly homogeneous building geometry and several gaps between buildings (**Figure 1a**). As seen in **Figure 1(b)**, some parts of the street have large architectural features such as balconies, which extend about a metre into the street. Morphological data was obtained from the Nicosia Master plan and the Department of Land and Surveys, Cyprus Ministry of the Interior.

Figure 1: Rigenis Heterogeneous Street Canyon
a) Schematic Diagram of Rigenis Street and of telescope mast positions in the street at three different cross sections along the length of the heterogeneous street, b) Rigenis Street View, showing the parked cars along the South side and traffic lane on the North side. The buildings are complex and have large balconies as well as variations in roof height

Reference data on background meteorological conditions were measured every second and averaged to a one-minute resolution on top of a mast on the roof at a height of 26m ($2H_{building}$) from the ground, using a La Crosse Technology WS-3502 cup anemometer and a mini weather station, at a resolution of 0.1m/s and 22.5 degrees for wind direction. Velocities in the street were measured with one 3D 8100 Young ultrasonic anemometer (accuracy for wind speed was ±0.1% rms, ±0.05m/s and for wind direction ±2^o for wind speeds up to 30m/s, sampled at 32Hz), and four 2D Gill Windsonic Ultrasonic Wind Sensors (accuracy for wind speed ±2% and for wind direction ±3^o up to 12m/s, sampled at 1Hz.).

Carbon Monoxide (CO) was chosen as an indicator of traffic related emissions within the street canyon because it has slow chemical transformation within the atmosphere and can be considered inert over short distances. The main source of CO was emissions from a continuous stream of cars and vans along the street. CO concentration was measured every 10 seconds via two types of electrochemical sensors, Learian Micro ICOM and Wireless Bracelet Nodes (see Shum et al, 2013).

Vertical profiles of flow fields and CO concentrations were measured at three cross sections of the street (noted in **Figure 1a**), with different local street geometry as follows. Building ratios are calculated assuming south-westerly perpendicular background wind:

- Section I: building ratio $H_{leeward}/H_{windward}$ =1, with surrounding buildings on the South side up to 27% taller and a wide gap between the buildings on the North side, and large balconies
- Section II: building ratio =1.92, and gaps near the buildings on both sides
- Section III: building ratio =1.28 and a gap on the South side, and large balconies on the facades on both sides of the street

To create the vertical profiles, the 3D and 2D anemometers and four CO sensors were spaced out along the telescopic mast, which was placed about 0.8 m away from the buildings and was gradually extended from the ground up to 12m height with a total capture time of 10 minutes for each profile. The measurements of vertical profiles were taken from 09:00 am until 12:30 pm, a time of day with relatively stable wind and traffic conditions. At each section, vertical profiles were obtained first on one, then the opposite side of the street after a 20 minute break between profiles for instrument set up.

A second field campaign was carried out, in which CO concentration levels were measured at street level on several days between 8:00am until 4:00pm. These CO sensors were deployed at the cross sections on both sides of the street, roughly 0.1m away from the building walls; six were positioned at a height of 1.5m from the ground, six at 2.5m from the ground.

2.2 Physical Modelling

2.2.1 Water Channel

The physical modelling was carried out in a low-turbulence atmospheric boundary layer water channel in the Pat Kemp Fluid Mechanics Laboratory at the Dept. of Civil Engineering at University College London (UCL). This open water channel is made of a level glass bed with connecting plate glass side walls, built onto a substantial cast iron main girder structure. The dimensions of the water channel are shown in **Figure 3**. To reduce undesirable turbulence at the inlet of the channel, the water is passed through five meshes and a shaped inlet fairing. The maximum water depth that can be reached is 0.22m, which was set as constant for all the simulations.

The maximum height of the physical model within the channel should be 40% of the depth of the boundary layer (or, the height of the free stream should be at least 2.5 the height of the scaled buildings). To create a suitable profile for a typical Urban Boundary Layer, it was necessary to increase the boundary layer thickness. A trip wire of 2mm diameter was placed at the inlet of the water channel, on the floor and side walls,. **Figure 2a** shows the development of the boundary layer profile of the empty water channel with and without the trip wire at 2.30m form the inlet and shows that the boundary layer thickness (BLT) without the wire is 40mm (calculated following Hansen (1930)) while with the wire the BLT reaches a depth of 60mm. The greater boundary layer thickness allowed us to introduce a larger scale model to better visualise the flow and the tracer dye dispersion inside the canyon. **Figure 2b** shows the development of the boundary layer and the fact that once it is developed, it remains stable. As a result the scaled model was sized to be up to 60mm high. Thus, the upstream bulk velocity of the empty water channel was 0.16m/s, resulting in a Reynolds number $3.5*10^5$ at a distance of 2.30m downstream of the inlet The similarity criteria suggested by Meroney et al. (1996), Hoydysh et al. (1974) and Snyder (1972) are satisfied in our experimental set up: The Re number at the cavity exceeds 3400 and the critical roughness Reynolds number, which depends on the roughness of the plate, is greater than 2.5. Full details of the physical model and boundary layer flume are provided in Karra (2012).

Figure 2: a) Velocity profile with and without trip within empty water channel, b) Development of Boundary Layer Profile within the water channel

2.2.2 Street Canyon Model

Following the previous measurements the upstream bulk velocity at $2.5H_{building}$ from the bottom of the bed was a constant 0.23 m/s and a Reynolds number above the buildings of 6.3×10^4. A 1:183 scale perspex replica of the Rigenis street canyon was placed in the water channel 2.24m from the inlet, such that the flow was perpendicular to the buildings, as shown in **Figure 3**. The street replica was the only region of interest for the purposes of this study; it was simplified to represent the large scale geometric shape of the buildings and thus features smaller than 1m scale, such as balconies, were not explicitly modelled. The street replica was aligned perpendicular to the flow and spanned across the water channel up to the walls, to avoid side wall effects. Three homogeneous roughness blocks of the same height and width were positioned upstream and two similar homogeneous roughness blocks were positioned downstream of the test street canyon in order to smooth the turbulence and to achieve the necessary fully developed urban boundary layer profile.

Figure 3: Configuration of the street canyons and Rigenis street model in the water channel and PIV and PLIF set up

2.2.3 Line Source Design and Imaging

A line source released dye to simulate the exhaust emissions from vehicles aligned along the street length. The design of the line source was based on that proposed by Meroney et al. (1996) with some modifications to enable application to water properties. Rhodamine 6G was chosen as a passive scalar and was injected through the line source placed at the bottom of the canyon at a constant flow rate, 8ml/min, through a syringe pump. Full description of the set up and the techniques are given by Karra (2012).

The study collected simultaneous measurements from PIV and PLIF, providing detailed two-dimensional information on velocity and concentrations at the three cross sections of the street canyon. The Laser system, a New Wave MiniLase double pulse Nd: YAG laser (532nm wavelength, power 100 mJ and pulse width 6ns) from TSI was placed vertically on top of the water channel at 0.70m from the bed surface up to the edge of the lens, and two CCD cameras were oriented perpendicular to the laser on both sides of the water channel and were connected to the laser pulse 610035 synchroniser to ensure that all components operated in the correct sequence. A TSI PowerView Plus 2048 x 2048 pixel CCD camera was used with a Nikon 60mm lens of 2.8D focal length for the PIV and a TSI PowerView Plus 1280 x 1960 pixel with 28mm Nixon lens of 2.8D focal length was used for the PLIF (Figure 2).

3. Results and Discussion

3.1 In-street airflow patterns for different background wind conditions

The presentation of the results in this field study is structured according to background wind direction in relation to the street canyon axis as observed at rooftop level. We first present the overall variability found in the field and identify several Intensive Observation Periods (IOPs) with different background wind conditions. We then present results for the different types of IOPs.

3.1.1 Variability of the background wind

Overall it was observed that the approaching wind above the heterogeneous canyon varied significantly throughout the daily observation period of eight hours, as seen in **Figure 4.** It was thus necessary to identify shorter duration IOPs during which the mean wind direction was relatively stable. A mean approaching wind direction was identified, as was its associated mean wind meandering (standard deviation from the mean direction), for several different IOP cases in the overall field study. Table 1 shows the five identified IOPs, as classified according to the measured Mean Wind Direction, of the background wind approaching at rooftop level. The street orientation is SE to NW (135° to 315°), and the background wind would have been exactly perpendicular to the street if it had approached from 225°(SW) or 45° (NE). We first discuss the cases of perpendicular wind, for both steady wind (IOP1, 2) and highly variable wind (IOP3, 5); then present the case for oblique background wind (IOP4).

Figure 4: Variability of reference background wind direction and velocity at 26m above the ground level: (a) perpendicular case; (b) oblique to perpendicular case (data recorded and averaged to one minute)

Table 1: Description of the five distinct Intensive Observation Periods (IOP cases).

3.1.2 Perpendicular prevailing wind and comparison with Laboratory model

Two IOPs were obtained in the field for a perpendicular South-Westerly prevailing background wind. IOP1 has a mean wind variability of 26.9^{o} and in this time period vertical profiles were obtained for Section I. IOP 2 had higher variability of 37.6^{o} and in this time period vertical profiles were obtained for Section II. The flow fields for the same sections under perpendicular steady flow conditions were obtained in the Laboratory. The results of these observation periods are shown in **Figure 5**, and are compared to the corresponding laboratory measurements. The figure shows the direction of the prevailing wind whilst the vertical profiles were being obtained, separately for each profile, and notes the direction of the reference flow in the laboratory. As the four different vertical profiles were obtained one by one, the wind had changed during the observation period and this is noted on the side of the figures.

In IOP 1, Section I, wind speeds were observed overall to be 60% lower on the Northeast side of the street – which was the windward side in this case - than on the Southwest side. The typical clockwise vortex expected to arise in street canyons is seen very clearly in the laboratory model in Section I under steady flow conditions. However, this vortex was not observed in the field study.

Figure 5: Reference background wind captured over the duration of recording vertical profiles in Section I and II
a) Section I, IOP1: i) wind measured during the vertical profile on the South side ii) velocity fields obtained in the field and underneath those the reference velocity fields obtained via PIV in the experimental model of the street iii) wind measured during the vertical profile on the North side
b) Section II, IOP2: i) wind measured during the vertical profile on the South side ii) velocity fields obtained in the field and underneath those the reference velocity fields obtained via PIV in the experimental model of the street (the grey shaded area represents a region of the street that was not visible to the PIV) iii) wind measured during the vertical profile on the North side

Section II has a complex geometry, due to the "step down" geometry created locally by the drop in building height on the windward side, as well as the gaps around the buildings. The reference flow field observed in the Laboratory does not develop a vortex. This is due to the flow being fully three dimensional at this cross section, and this illustrates the very localised nature of the effect of geometry on airflow in the street. This three dimensional flow was seen clearly in the laboratory under steady flow conditions (as further discussed in section 3.3.2), but in the observation period IOP2, under realistic variable wind conditions the vertical profile observations do not match those obtained in the Laboratory. It is clear from the results in both sections, that real world conditions are so variable that the vortex flow, which is the hallmark of street canyon research and the main reason street canyons are considered unfavourable for ventilation, does not always appear. This is an encouraging result in terms of street ventilation.

3.1.3 Highly Variable wind

Flow fields were observed at Section III of the street canyon for two cases: IOP3, where there is perpendicular wind both from NE and from WSW (coming from the opposite side of the street compared with the reference case), is shown in Figure 6a; and IOP5 for highly variable wind that fluctuates from perpendicular to parallel in the observation period is shown in **Figure 6b**. (Note: during the measurements in Section III we did not observe a perpendicular prevailing wind comparable to the ones experienced for Section I and Section II, thus a laboratory reference case is not shown here; for reference it can be seen in **Figure 11**). In the cases of highly variable wind under realistic field conditions it was not possible to observe a vortex formation at all. The airflow pattern is not much different than in the case where flow was relatively steady and perpendicular. It is seen that in reality, the relative steadiness of the background wind does not seem to have a great effect on the in-street airflow and the conditions on the ground.

Figure 6: Variable wind cases, vertical profiles captured in the field in Section III:
a) IOP3: i) Reference background wind over the duration of recording vertical profiles on South West side ii) Vertical profiles of velocity in the field iii) Reference background wind over the duration of recording vertical profiles on South West
b) IOP5: i) Reference background wind over the duration of recording vertical profiles on South West side ii) Vertical profiles of velocity in the field iii) Reference background wind over the duration of recording vertical profiles on South West side

3.1.4 Oblique wind

Measurements were also taken in Sections I and II of the street for IOP4, in which case the prevailing approaching wind was oblique to the street axis (**Figures 7a and 7b**). The wind was relatively stable during the capture period of the profiles in both cross-sections. Yet the flow fields were quite different from what is predicted in the literature (e.g. Oke, 1998). The measured airflow patterns on the SW side of the street are quite similar for both cross sections, which have very similar background wind conditions in the field. However, the measurements are quite different on the NE side of the street, which in Section II, produces a “step-down” geometry. This illustrates the effect of heterogeneity of the street on the flow fields.

Figure 7: Oblique wind - vertical profiles captured in the field during IOP4:
a) Section I: i) Reference background wind over the duration of recording vertical profiles on South West side ii) Vertical profiles of velocity in the field iii) Reference background wind over the duration of recording vertical profiles on South West side
b) Section II: i) Reference background wind over the duration of recording vertical profiles on South West side ii) Vertical profiles of velocity in the field iii) Reference background wind over the duration of recording vertical profiles on South West side

3.2 Quantitative comparison between velocities in the lab and field measurements

A quantitative comparative analysis was conducted for the air flow velocity fields obtained in the urban field measurements and the corresponding laboratory simulations, in order to assess quantitatively the degree of influence on the flow velocity fields due to the real field conditions as opposed to those in a controlled physical simulation in the lab. This was conducted only for the IOP cases IOP1 and IOP2 - for relatively stable perpendicular background wind. The corresponding laboratory velocities were normalized through the Reynolds number similarity. This analysis was carried out following the methodology used by Neophytou et al. (2011) for comparing urban field measurements and corresponding numerical simulations in the Joint Urban 2003 field campaign in OKC- U.S.A.

For a collective view of IOP cases IOP1 and IOP2, **Figure 8** shows the scatter plots of the wind direction and wind speed as observed in the field in comparison with the laboratory measurements. The dotted lines in the figures depict the bounds of interest within which the variability is assessed; for the wind direction the bounds are set within 45°, while for the wind speed the bounds are set for values within a factor of 2 (i.e. between 1/2 and 2). The figures distinguish amongst measurement points located at different sides of the street canyon (NE versus SW side). The total fraction of the measurement points falling within the bounds is calculated. **Table 2** presents these fractions in terms of the assessed IOP cases IOP1 and IOP2, which refer to observation periods at cross-sections I and II respectively.

We observe that lower wind variability does not necessarily ensure a better agreement between the wind direction measured in the field and in the lab. This is consistent with the findings in section 3.1. As seen in **Table 2**, only a 27.3% fraction of the wind direction measurements at cross section I (IOP1) was found to be within ±45 degrees of the corresponding laboratory measurements despite having lower variability in the mean rooftop wind direction (26.9), while at cross section II (IOP2), the corresponding fraction was found to be 45.5% and the variability was (37.6). It may also be that the airflow was much more affected by the particular local street features and complex architectural features in cross section I, which had building extrusions and large balconies that were not present in the simplified physical model tested in the laboratory.

Regarding the wind speeds, the situation is reversed: for IOP1 a 36.6% fraction of the wind speed data from the field measurements and the corresponding laboratory measurements was found to be within a factor of 2 agreement, whereas a smaller fraction, of 22.7 %, falls within a factor of 2 for the IOP2 case. The lower agreement for IOP2 (compared to IOP1) persists when we re-consider the fraction for the wind speeds only above a threshold value of 0.05m/s, which is the threshold value of the instrumentation. It is interesting that the case with the lower agreement (IOP2) takes place at Section II, which is more homogeneous and has less obstructions and architectural features compared to the other sections, but which is a "step-down" configuration in which a vortex would not be expected to form, and has not been formed in the laboratory.

The data is also calculated and presented in **Table 2** in terms of the Windward or the Leeward side of the street canyon. The Windward side of the street-canyon shows a better agreement than the Leeward side of the street-canyon for the wind direction, but no marked difference in agreement for the wind speeds. It must be noted however that the fraction of measurements above the accuracy threshold is substantially lower on the windward side (only 7.7%) therefore this result may not be conclusive yet and merits further testing in future field campaigns.

Figure 8: Scatter plots for (a) the wind direction measurements and (b) the wind speed measurements as observed in the field measurement campaign and in the corresponding laboratory measurements for two observation periods - IOP1, IOP2.: i) IOP1 is at Section I ($H_l/W=1.12$, $H_w/W=1.12$), and ii) IOP2 is at Section II ($H_l/W=1.25$, $H_w/W=0.75$), The plotted dotted lines show the bound lines within $\pm 45^o$ (for wind direction) and within a factor of 2 (for wind speed)

Table 2: Fraction of points included within the bounds for IOP I and II – calculated separately for section I, section II and for the Windward side in both sections and the Leeward side in both sections

3.3 Pollution Distribution

3.3.1 Relationship between street level CO concentrations and background wind direction

Carbon Monoxide was measured during along the length of the street. First, results of a measurement period of one hour in Section II, in the middle of Rigenis street are shown. **Figure 9** shows the CO concentrations at one minute averages at a height of 1.5 metres from the ground in the middle section of Rigenis street canyon as a function of rooftop wind direction (wind from the north corresponds to 0^o and wind perpendicular to the street corresponds to 225^o) for a measurement period of one hour. Within this one hour, the wind meandered between predominantly perpendicular, oblique and parallel to the street. It can be seen that there is no wind direction that is clearly associated with higher pollution episodes. This variability is consistent with the results of the velocity measurements, and is determined by the full set of parameters influencing the street, such as the variation in wind speed and traffic levels in the street at the time of the measurements. Overall, the wind variability in real field conditions is so high that background wind direction at rooftop height does not dominate the pollution concentrations in the street.

Figure 9: Relationship between CO levels and wind direction in Section II; shown on the left are results observed on the South West side and to the right, results from the North East side of the street. The measurements for perpendicular wind to the street episodes and for parallel wind episodes are noted on the figure.

The following results are from a second field campaign in which CO concentration levels were measured at street level on several days between 8:00am until 4:00pm. Concentration levels were measured at several locations along the street length, as seen in the diagram in Figure 10b. **Table 3** presents the second set of IOP cases, showing the eight hour average background wind conditions recorded on the rooftop, during the campaign.

Table 3: IOP cases for pollution dispersion measurements

Figure 10a presents the mean CO concentration levels for each IOP case. These are averaged from all measurements along the length of the street at heights of 1.5m, and 2.5m from the ground. Because of the high variability of the wind, results are shown for the time period within those eight hours of measurements in which steadier conditions occurred.

On the whole, for all IOP cases the CO concentrations are greater in the middle of the canyon, Section II, as compared with Sections I and III, which are nearer the junctions at the ends of the street. The only exception is the high concentrations observed in Section III at 1.5 m height on the SW side of the street. This site is unique as there are no gaps in the street canyon near that measurement location and this might explain the higher concentrations there.

Figure 10: a) Mean Concentration levels along the street for all IOP cases; (i) South West side and (ii) North West side b) Schematic diagram of measurements positions

For all IOP cases the concentrations are systematically higher at 1.5m height by 20% to 50% than at 2.5m height, demonstrating that pedestrian exposure near the ground can be significantly higher than expected from rooftop measurements.

For the case of persistent oblique wind in IOP4, the CO mean concentrations were lower overall by 20-30% compared to the partly oblique flow in IOP3. However, IOP presented higher concentrations in most locations than for IOP2, contrary to the expectation, in symmetrical canyons, that CO concentrations for oblique directions would be always lower than for perpendicular flow (Vachon et al., 2000). This might be as a result of the meandering of the wind during the measurement period, the specific traffic rate and levels during that period (Karra et al., 2011), or due to the heterogeneity of the street.

3.3.2 Flow and dispersion in the laboratory

The experimental study enabled very detailed simultaneous observations of flow and concentrations for the reference case of steady perpendicular wind under controlled conditions. **Figure 11** presents the mean velocities and concentrations at the three cross sections inside the heterogeneous street. The flow is perpendicular to the street, entering at rooftop level from the left. Great differences between the cross sections are found in both the airflow and the pollution concentrations. **Figure 11a** shows the velocity and concentration field in Section I. There is mass transfer from the windward building to the leeward building resulting in the accumulation of pollution near the wall of the leeward building. This leads to Leeward concentrations which are twice as high as those on the wall of the windward building.

Under the conditions of steady flow in the lab, there are robust, systematic differences in concentrations between the different sections and sides of the street. **Figure 11b** shows that Section II produces a different flow pattern than typically found in symmetrical street canyons, which results in enhanced mixing and a more homogeneous distribution of pollutants in the street. Pollution concentrations at the top of the leeward building are 60% lower than at the bottom of the canyon. Section III, seen in **Figure 11c**, shows a flow pattern that is more similar to the symmetrical canyon, due to the small ratio of H_l/H_w. Again, towards the leeward building the concentrations are twice as high as those near the windward wall. The table in **Figure 11e** presents the total mean concentration over the same domain from z=0mm up to z=60mm, for all cross sections. We find the mean concentration is lowest in Section I, followed by Section II, while Section III accumulates concentrations more than twice as high as those in Section I.

In the laboratory, which corresponds most closely to the field study IOP case IOP2, we observed greater concentrations always on the leeward side, as seen in **Figure 11a, 11b, 11c**. Yet, in the field, the mean concentrations were always greater only on side of the street, on the NE side, for **all** IOP cases and at both measurement heights. This was true both for the case of IOP2, IOP3, and IOP4 when the NE side was the windward side, and for IOP1, when the NE side was the leeward side. Thus, this higher concentration on the NE side of the real street was in effect whether the wind was perpendicular, oblique or meandering and regardless of the direction the wind was approaching from. This indicates that maybe a local parameter in the street that did not appear in the experimental model, has a higher effect on concentrations. It is likely that this anomaly relates to the traffic lane in the real street not being exactly in the centre of the street but closer to the NE side. It may also be because of the line of parked cars on the SW side.

Instantaneous velocity and concentration fields (period of time from 0.0004s to 1.98s) are shown in **Figure 11d**. The vortex that can typically be seen when calculating the average values for steady flow is not seen clearly here, and observations over a time series in the experiment show this vortex dissolving and reconstructing at short intervals. This instantaneous image is a good representation of field conditions as background wind meanders or changes speed.

Figure 11: Velocity and concentration fields in the heterogeneous street canyon.
In the grey area, vectors and concentrations were not visible to the PIV and PLIF systems due to the higher buildings obstructing the view and velocities and concentrations could not be measured: a) Section I, b) Section II, c) Section III and d) instantaneous measurements of velocity field and concentration levels in Section II, e) **Table 4**; Mean concentration levels in heterogeneous street canyon

The heterogeneous street, with uneven building heights along the length of the street and gaps between buildings, shows marked three dimensional flow patterns. This can be seen clearly in **Figure 12,** which presents the velocity fields on three horizontal planes as visualised from above, at 8mm, 30mm and 50mm from the bottom of the bed. There is significant channelling through the gaps in the buildings.

Figure 12: Velocity fields at three horizontal planes along the length of the heterogeneous street a) at 8mm from the bottom, b) at 30mm from the bottom, c) at 50mm from the bottom, d) Position of the measurements on the model of the street canyon

4. CONCLUDING REMARKS

In this work we investigate a heterogeneous real urban street canyon using a series of field measurements and controlled laboratory experiments and attempt to measure and analyse all its complexities, to account for both the real heterogeneity in the geometry and the real field conditions including great wind variability. The complementarity of the field campaign and the physical model have afforded us a deeper understanding of a wide range of issues of importance to street canyon ventilation, and have demonstrated just how complicated air flow and pollutant dispersion processes can be in real street canyons. To our knowledge, such a dataset (i.e. accounting for both the geometric complexity, the wind variability and the combination of air flow and pollutant concentrations) has not been reported so far. There is a comparative study between laboratory and field measurements over an idealized, homogeneous urban street but not in a highly heterogeneous real urban canyon. Furthermore, our study reports comparative results for both the airflow and pollutant dispersion fields – for such a real canyon; so far only airflow results have been compared in some other case studies.

Field measurements of wind velocities and Carbon Monoxide (CO) concentrations were taken under real field conditions in Rigenis Street in Nicosia city centre (Cyprus), at several cross-sections along the length of the street (each cross-section being of different aspect ratio). A physical model of the same street was produced for the purpose of laboratory experiments, of necessity making some geometrical simplifications of complex volumes and extrusions. The physical model of the street was tested in an Atmospheric Boundary Layer water channel, using simultaneously Particle Image Velocimetry (PIV) and Planar Laser Induced Fluorescence (PLIF), for flow visualisation as well as quantitative measurement of concentrations and flow velocities. The experiments demonstrated the effects of large scale street heterogeneity on airflows in this type of street canyon, and how they differ from those expected in a symmetrical, homogeneous street canyon. The variable wind field conditions were represented by a steady mean approach velocity in the laboratory simulation. The real field background wind was in fact observed to be highly variable; thus different intensive observation periods represented by a different mean wind velocity and different wind variability were defined. The laboratory investigations (essentially representing periods of near-zero wind variability) showed a clear sensitivity of the resulting flow field to the local geometry and substantial three-dimensional flow patterns were observed throughout the modelled street. The real-field observations and the laboratory measurements were compared for the cases of perpendicular flow observed in the field.

Overall, we found that lower wind variability does not necessarily ensure a better agreement between the airflow velocity measured in the field and in the lab. In fact, we believe that in certain cross sections, the airflow was more affected by the particular, local street geometry and complex architectural features such as building extrusions and balconies (which were not represented in the simplified physical model tested in the laboratory), than by the real wind field variability. For wind speed comparisons the most favourable agreement (36.6% of the compared values was within a factor of 2) was found in the case of lowest wind variability in the section closest to the physical lab model; for wind direction comparisons the most favourable agreement (45.5% of the compared values was within $\pm 45^{o}$) was found in the case with higher wind variability but in the cross-sections with more homogeneous geometrical features.

Street canyon studies are always limited by the necessity to reduce complexity of real streets when laboratory scale studies are conducted. This study is no different, and it is possible that a better agreement would have been achieved if the physical model were a more exact replica of the surrounding streets. However this study attempts to show that these complexities and heterogeneity do make a difference by accounting for large scale features and by conducting very detailed flow visualisation. Field studies in street canyons are severely limited by resources and time constraints; by necessity this study provided a snapshot of the conditions in a real street at a few particular times. It is seen that by conducting both studies, a more comprehensive picture of the airflow and pollution concentrations that can be expected in that street can be constructed, and some general observations about the impact of street heterogeneity and wind variability can be made.

More specifically we have found that:

1. Realistic wind conditions were found to be highly meandering throughout the day. This should have had a demonstrable effect on flow patterns measured in the street, on formation of the vortex, and on pollution concentrations. Yet a quantitative analysis comparing local air velocities in the field and in the lab finds low agreement even when background wind is stable, during short Intensive Observation Periods. We find that in the field, airflow patterns do not relate clearly to background wind speed, direction, and variability within an observational time period. In the laboratory, we find systematic differences in pollution concentrations between different sections and sides of the street; yet under real

conditions, variability in the street measurements is high. This raises questions about vortex formation in real streets and its impact on the ventilation of real streets.

2. The laboratory study demonstrates the effects of heterogeneity on airflow and pollution distribution, with substantial three dimensional flow patterns throughout the street, and a clear sensitivity to local geometry. The street canyon's aspect ratio as a whole does not explain the flow patterns found in this case. We find that simplification of a real street to a homogeneous street canyon in models and simulations needs to be done with caution.

3. As some of our field observations cannot be explained only by overall street geometry or by wind intensity and direction, it seems possible that local street parameters have a significant effect on flow and dispersion: the position of the traffic lane, the presence of parked cars and the presence of large balconies, all might affect the flow. We observe that CO concentrations are always greater on the NE side of this street, regardless of the direction of the background wind. This is most likely due to the location of the traffic lane being closer to the NE side of the street and demonstrates a high sensitivity inside the street to this local parameter.

4. We observe a couple of noteworthy results of the field campaign that raise issues of concern for pedestrian exposure to traffic related pollution in all types of street canyons: that concentrations are almost always higher in the middle of the street, away from the junctions. And that in all cases, pollution concentrations were systematically higher at the height of pedestrians, 1.5 m, than they were at 2.5 m height.

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