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ESTIMATION OF SCALAR FLUXES WITHIN MODELLED INTERSECTION DEPENDING ON THE APPROACH FLOW DIRECTION

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Abstract: Increasing vehicle traffic emissions seriously deteriorates dispersion conditions in big cities. In built-up areas street intersections represent regions of pollutant exchanges between street-canyons. The objective of this study is to investigate the influence of the approach flow direction on contaminant spreading within an intersection in an idealised symmetrical urban area. Mean velocity fields and mean concentration fields are measured at a model of urban area in wind tunnel for several wind directions. Advective scalar fluxes in horizontal and vertical direction are computed from measured data for every flow direction to quantify pollutant spreading. The requirements of the similarity of a real atmospheric boundary layer and a model boundary layer in the wind tunnel are satisfied. Results of the experiment show a significant sensitivity of measured quantities within the intersection on the approach flow direction thus the approach flow extensively influences contaminant spreading within the built-up area. The highest contaminant concentrations and fluxes are measured in the bottom parts of street-canyons. The important role of the vertical turbulent scalar flux in street-canyon ventilation is expected because of non-zero sum of all measured advective fluxes within the intersection. The 15° flow direction was found to be the most favourable dispersion conditions in the studied area.

Key words: *air pollution, atmospheric boundary layer, physical modelling, contaminant spreading, scalar fluxes, intersection*

INTRODUCTION

Vehicle traffic pollutants emitted directly to street-canyons can cause serious danger for people in large urban areas. As shown in (Robins A. *et al.*, 2002) and (Wang X. and K.F. McNamara, 2007), street intersections represent regions of pollutant exchanges between street-canyons and their geometry play an important role in pollutant dispersion and ventilation of urban areas. The objective of this study is to investigate the influence of the approach flow direction on contaminant spreading within an intersection in an idealised symmetrical urban area. The model of idealised urban area was designed after the common European inner-city area with apartment houses with pitched roofs. Regular blocks of 24 m high apartment houses form perpendicular arrangement of street canyons and intersections (see scheme in Figure 1). The wind tunnel model has been scaled down to 1:200. We consider characteristic obstacle height H = 20 m as a height of building walls to the bottom edge of roofs. Characteristic obstacle length L = 20 m is a width of street canyons.

EXPERIMENTAL SET-UP

The experiment was conducted in a low-speed open-circuit aerodynamic tunnel at the Institute of Thermomechanics AS CR in Nový Knín. A fully turbulent boundary layer was developed by a 20.5 m long section of the tunnel equipped with spires and roughness elements. The test section of the tunnel is 2 m long, 1.5 m wide and 1.5 m high. For flow measurements two-dimensional optical fibre laser Doppler anemometry (LDA) was used. Concentration was measured using slow-response flame ionisation detector (FID) with ethane used as a tracer gas. Ethane is a passive and non-reactive gas with its own density close to the density of the air. The tracer gas simulating traffic pollutants was emitted from a point source placed at the bottom of a street canyon in front of the studied area.

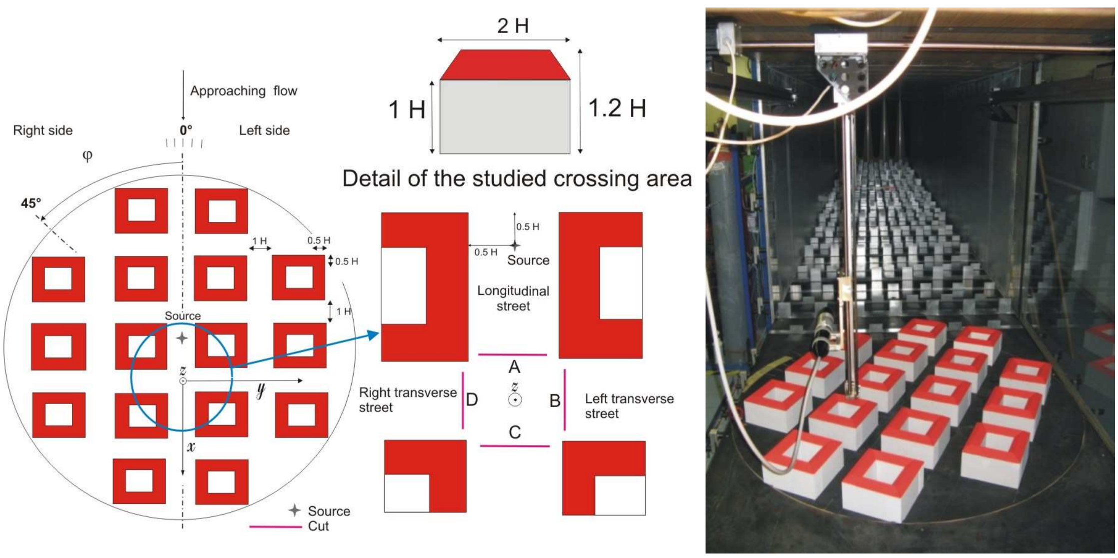

Figure 1. Scheme of built-up area model, studied X-shaped intersection and the photograph of the model placed in the wind tunnel. Street aspect ratio was L/H = 0.83, where L is width of the street and H is the characteristic height of buildings. The width of buildings was 0.5H.

A vertical profile of turbulent flow characteristics was measured above the measuring position under neutrally stratified conditions (see Figure 2). Measured velocity data were fitted by the logarithmic and power law. Roughness length and zero plane displacement were obtained from mentioned fit by the logarithmic law. The exponent α was determined by fitting the power law. This corresponds according to (Britter R.E. and S.R. Hanna, 2003) and (ASCE, 1995) to parameters for boundary layer flow above a densely built-up area without much obstacle height variation - roughness length z_0 = 1.1 m, displacement d_0 = 8.5 m and power law exponent α = 0.3 in full scale.

To verify requirements for Townsend hypothesis, see (Tennekes H. and J.L. Lumley, 1972) or (Townsend A.A., 1976), the critical Reynolds building number was found. Building Reynolds number is given by

$$\mathrm{Re}_B = \frac{U_{2H} H}{\nu}, \tag{1}$$

where ν is kinematical viscosity, U_{2H} means a characteristic reference velocity measured at high $z = 2H$. The experiment was carried out by building Reynolds number Re_B = 18 000 that lies on the lower edge of interval for valid Townsend hypothesis. Relevant free stream velocity was 3 m.s^{-1}.

RESULTS

To quantify spreading of vehicle emissions within the street canyons horizontal velocity of flow and concentration of tracer gas were measured in vertical cuts (cross-sections) placed at outfalls street canyons connected to the studied crossing (see Figure 1). Furthermore, vertical velocity and concentration were measured in a horizontal plane at roof level ($z = 1.2H$) above the crossing. Results were obtained for 5 different values of the angle of approach flow angle φ = 0°, 5°, 15°, 30° and 45°. From velocity and concentration values scalar fluxes of passive contaminant were computed.

Due to an understandable image of results we used a transformation of the measured three-dimensional grid to a horizontal plane (see Figure 3). Vertical cuts of the measured grid were tipped out to the horizontal plane given by the roof level of the crossing. An orientation of velocity vectors in the vertical cuts was maintained in the horizontal plain image because we measured only horizontal velocity there.

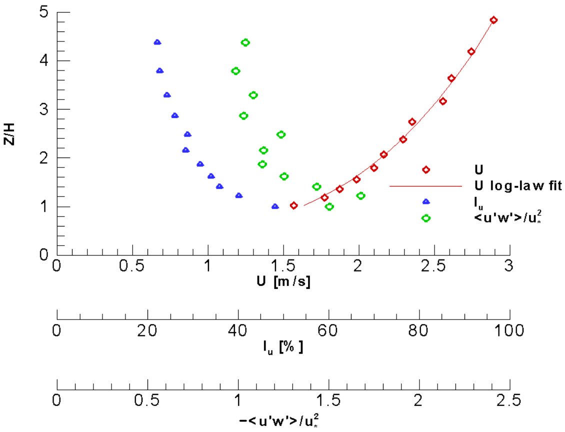

Figure 2. The vertical profile of turbulent characteristics above the studied area

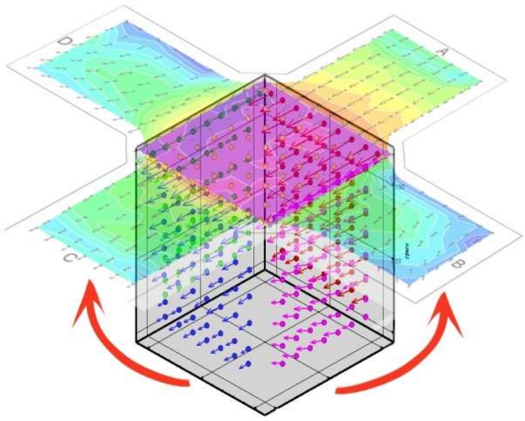

Figure 3. The scheme of trans-formation of the measured 3-D grid to the horizontal plane.

Velocity field

The flow inside the canopy is strongly three-dimensional and vortexes of various scales are formed within and above the canyons and crossings. Measured velocity field is represented by dimensionless horizontal velocity U^* and vertical velocity W^* given by

$$U^* = \frac{u}{U_{2H}}, \qquad W^* = \frac{w}{U_{2H}}, \tag{2}$$

where u and w are measured horizontal and vertical components of velocity, U_{2H} means a characteristic reference velocity measured at high $z = 2H$. A contour plot of scalar values was added to images of velocity field.

Concentration field

The dimensionless concentration C^* for a tracer emitted from a point source was obtained from formula (ASCE, 1995) by

$$C^* = \frac{C U_{2H} H^2}{Q}, \tag{3}$$

where C means measured concentration, U_{2H} means velocity at the height $z = 2H$ and Q is a source emision.

Flux field

To better quantify spreading of traffic emissions within street-canyons we computed a relative dimensionless flux of passive contaminant (further only flux) F^* by

$$F^* = U_i{}^* C^*, \tag{4}$$

where $U_i{}^*$ is the component of dimensionless velocity perpendicular to the given plane and C^* is dimensionless concentration - see similar approach in (Belcher E.S., 2005) and (Robins A., 2009). This flux expresses a rate of emissions spreading through a unit plane caused by an advective transfer.

For images of flux fields we use this convention of signs: the positive sign means flux outward from the crossing area to the street-canyons or upwards and the negative sign means flux inwards or downwards the crossing area. For better understanding horizontal velocity vectors were added to flux field images.

We can observe quite asymmetrical flux field by φ = 0° (Figure 4). There is a higher flux into the right transverse street – cut D than into the left transverse street – cut B. This is probably caused by a small geometrical deviation of the model. However, it means very strong sensitivity of the whole system to the border conditions. Notice a negative, i.e. downward, flux on the top. A roughly inverse spread flux field is formed by φ = 5° (Figure 5) compared to the case φ = 0°. We can see a significant transport to the left transverse street – cut B. The lowest fluxes were measured in case of φ = 15° case within the studied area (Figure 6). Emissions were transported mainly to the left transverse street – cut B. There is an area of the positive flux on the right side of the top of the crossing. We got similar flux field for φ = 30° (not shown), but with higher flux values. A spreading of emissions mostly to the left side still predominated by φ = 45° (Figure 7). We measured an increase in flux especially it the left transverse street – cut B. There is mostly positive flux on the top of the crossing, but the magnitude of it is insignificant.

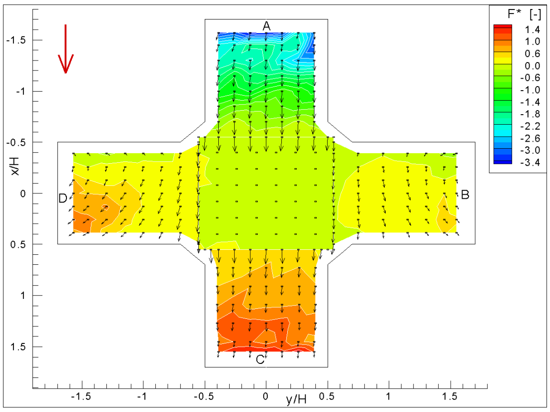

Figure 4. Relative dimensionless flux of passive contaminant field for approach flow φ = 0°.

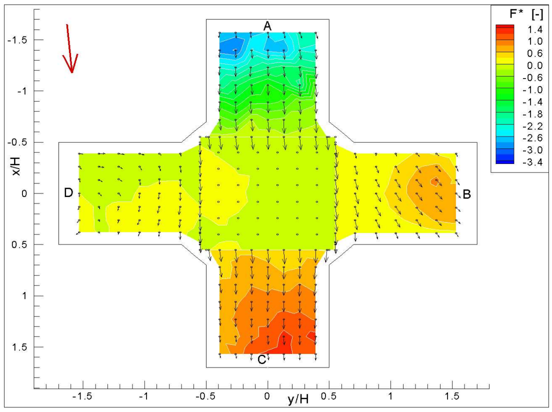

Figure 5. Relative dimensionless flux of passive contaminant field for approach flow φ = 5°

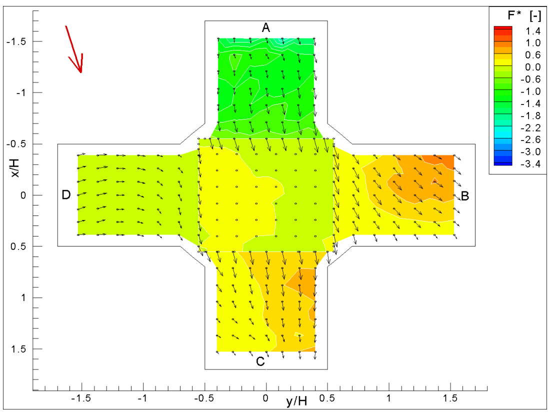

Figure 6. Relative dimensionless flux of passive contaminant field for approach flow φ = 15°.

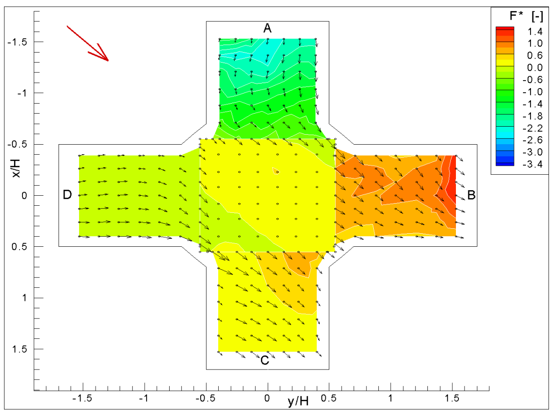

Figure 7. Relative dimensionless flux of passive contaminant field for approach flow φ = 45°.

For getting an information about absolute values of dimensionless flux of passive contaminant in different parts of studied area we computed an absolute dimensionless flux of passive contaminant (further only absolute flux) $F_A{}^*$ by

$$F_A^* = A^* U_i C^*, \tag{5}$$

where A^* is dimensionless area where U_i^* and C^* were measured. The convention of signs is the same as for relative dimensionless flux F^*.

The comparison of absolute fluxes in cuts areas within the studied intersection is shown in Table 1. We can observe an asymmetrical distribution of pollutant in cuts B and D for φ = 0°, that corresponds to Figure 1. Notice a significant decrease of absolute flux in cut D from φ ≥ 0°. The comparison between fluxes in cuts B and C is interesting for different values of φ. We observe the strongest stream of pollutant in cut C for φ = 0° and φ = 5°, but there is the highest flux in cut B for φ = 15°, 30° and 45°. Values of absolute flux in cut A for different wind directions shows a significant decrease of flux by φ = 15°. Take a note of similar distribution of pollutant into cuts B and C in this case so we can anticipate good dispersive conditions within the intersection. Measured values of absolute vertical flux in cut TOP are negligible compared to horizontal fluxes so this flux influences ventilation of the intersection insignificantly.

It's obvious that the sum of absolute fluxes in all cuts for every wind direction is negative (see the last column in Table 1). It means there must be extensive escape of pollutant from the intersection. Measured flux represents only advective transfer of pollutant so we can expect an extensive transfer of pollutant by turbulent transfer especially through the top area of intersection.

Table 1. Absolute dimensionless flux of passive contaminant field computed for full areas of cuts in studied intersection

φ	Cut	A	B	C	D	TOP	A+B+C+D+TOP
0°	F_A^*	-1,99	0,1	1,07	0,34	-0,03	-0.50
	%	-100%	5%	54%	17%	-2%	-25%
5°	F_A^*	-1,96	0,46	1,04	-0,05	-0,02	-0.53
	%	-100%	23%	53%	-3%	-1%	-27%
15°	F_A^*	-1,47	0,56	0,48	-0,07	-0,01	-0.50
	%	-100%	38%	33%	-5%	-1%	-33%
30°	F_A^*	-1,79	0,88	0,37	-0,05	0,05	-0.54
	%	-100%	49%	21%	-3%	3%	-30%
45°	F_A^*	-1,93	1,01	0,39	-0,15	0,07	-0.62
	%	-100%	52%	20%	-8%	4%	-32%

Because of computing absolute fluxes in different parts of vertical cuts in studied intersection we divided every vertical cut into three parts. Absolute fluxes in bottom part of cuts with vertical extent from $0H$ to $1/3H$ are shown in Table 2. First of all compare values of absolute fluxes in Table 1 to values in Table 2. Absolute fluxes in the bottom third of canyons are about 30-55% of absolute fluxes in full cuts. Distribution of absolute fluxes to individual cuts for different wind direction is similar to distribution in Table 1 - we observe a main stream of pollutant in cut C for φ = 0° and φ = 5°, but there is the highest flux in cut B for φ = 15°, 30° and 45°.

Table 2. Absolute dimensionless flux of passive contaminant field computed for the bottom part of cuts in studied intersection

φ	Cut	A	B	C	D
0°	F_{Ab}^*	-1.07	0.03	0.45	0.19
	%	-100%	3%	42%	18%
5°	F_{Ab}^*	-1.02	0.23	0.42	-0.02
	%	-100%	23%	41%	-2%
15°	F_{Ab}^*	-0.58	0.24	0.13	-0.03
	%	-100%	41%	23%	-5%
30°	F_{Ab}^*	-0.64	0.38	0.11	-0.01
	%	-100%	59%	18%	-2%
45°	F_{Ab}^*	-0.81	0.39	0.10	-0.04
	%	-100%	49%	12%	-5%

CONCLUSION

The described wind tunnel experiment quantified traffic pollutant diffusion at the X-shaped intersection in an idealised symmetrical urban area depending on the direction of approach flow. We found high sensitivity of the flow pattern within street-canyons to the approach flow direction. The highest concentration of traffic pollution occurred in bottom levels of streets. We computed relative and absolute dimensionless fluxes of passive contaminant to better quantify advective transport of traffic emissions within street-canyons. Values of fluxes showed spreading of pollution mostly within the running street with the source found for small angles of approach flow $\varphi \leq 5°$. We observed spreading of pollution mostly to the transverse street down the wind by angles $\varphi \geq 15°$. Absolute fluxes in the bottom thirds of the street canyons reached up to 55% of fluxes computed for the whole cross-section of canyons. We estimated a significant role of the vertical turbulent flux in street-canyon ventilation because of non-zero sum of all measured fluxes within closed area and negligible vertical advective flux of passive contaminant measured in the horizontal plane above the studied intersection. The best dispersive conditions in the studied crossing were measured for approach wind angle 15°.

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