# THE INFLUENCE OF TRAFFIC EMISSION ON IAQ, ESPECIALLY IN STREET CANYONS

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## ABSTRACT

Traffic emissions have a significant impact on urban air quality, which particularly concerns street canyons, i.e. spaces with limited air exchange. Traffic emissions in street canyons create high concentrations of air pollutants. Based on measurements carried out for selected routes and model experiments conducted in a wind tunnel, it is shown that a roadway's urban structure has a significant impact on concentrations of pollutants from traffic emission which enter buildings by means of mechanical and natural ventilation systems. In the case of buildings in a narrow street canyon pollution concentrations close to ventilation air intakes may be several times higher than in buildings in wide roadways. The paper also describes a possibility of identifying building surfaces that are particularly exposed to being infiltrated by traffic pollutants from adjacent streets.

## KEYWORDS

Vehicle emission, street canyon, urban air quality

## 1 INTRODUCTION

Among factors that determine indoor air quality (IAQ) chemical composition of air and concentration of fine particles $PM_{2,5}$ have a special significance as quantities which are difficult to control, which is the case for temperature and humidity. If it is assumed that the subject of analysis does not concern industrial sites indoor air pollution concentration values are influenced by:

- Internal factors, such as furnace emissions (e.g. gas cookers) and other technological processes, emissions from dividing structures and fittings, human emissions, flows from other closed spaces,
- External conditions such as local air pollution concentration values and their changeability in time and space, meteorological conditions including wind direction and velocity,
- Ventilation systems,
- Urban structures of buildings and their surroundings.

Indoor air pollution levels are of particular concern because most people (especially in towns and cities) spend 80 to 90% of their time indoors. According to the Environmental Protection Agency (EPA, 2011) indoor pollution levels may be 2-5 times, and occasionally, much higher than outdoors levels. A rise in concentration of certain air pollutants is caused by increased use of more synthetic materials for building and furnishings, use of more chemically formulated personal products in the more air tight buildings with reduced ventilation rates to save energy. Pollutants generated indoors are accompanied by those coming from the outdoor environment, including sulphur dioxide, nitrous oxides, fine and ultra fine PM, volatile organic compounds VOCs, and tropospheric ozone. Ventilation systems used do not alter the chemical composition of inlet (external) air. For ventilation of houses by opening the windows Schembari et al. (2013) found a high statistically significant correlation between personal exposure to $NO_x$, $NO_2$ and $PM_{2,5}$ and indoor and outdoor levels of these pollutants in Barcelona. Jensen et al. (2009) presents the results of $NO_2$, $NO_x$ and $PM_{2.5}$ concentration measurements in various New York City's boroughs and demonstrates slight differences in concentration values of outdoor and indoor air with considerable differences among particular boroughs. Vincent et al. (1997) compares indoor air quality in office buildings with different ventilation systems and pays attention to approximate values of average concentrations of $CO_2$, CO and particles for systems with natural ventilation, fan coil units and HVAC, and the approximate value of the indoor $CO_2$/outdoor $CO_2$ ratio equalling 1.9-2.1 for particular systems.

Urban air quality is diversified and depends not only on the kind and value of pollution emissions, but also on the technical conditions of emissions and the urban structure of a given area. Buildings are responsible for the disturbances in the air flow. The horseshoe vortices can be generated over the upper and side edges of a building as well as the lower part of the windward side. At the lee side the wake region and the cavity recirculation region are generated with a reduced air change. According to Peterka (Peterka et al., 1985), the cavity region can approach $z$=(2-2.5)$H_B$ in the range $x$=6$H_{B,}$ while the boundaries of the wake region can approach $z$=3$H_B$ in the range $x$=16$H_B$, where $H_B$ is the height of a building. Point-source and line-source pollutions (short chimneys and vehicle routes, respectively) emitted in this space cannot disperse freely, which may lead to high pollution concentrations (Bagieński, 2008, Ahmad et al., 2005, Meroney et al., 1966). Figure 1 shows a visualisation of a fume flow in a wake effect carried out in a wind tunnel (Bagieński, 2010).

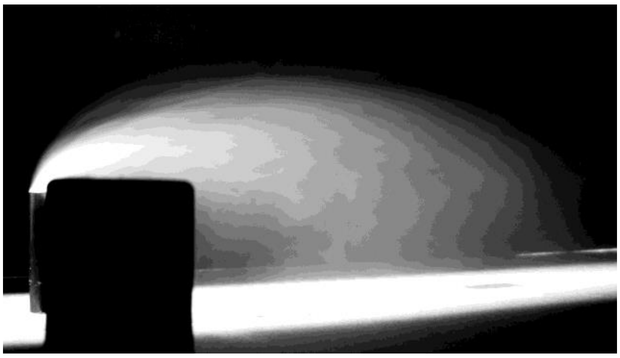

*Fig. 1 Disturbed fume flow, short chimney on the windward side of a building*

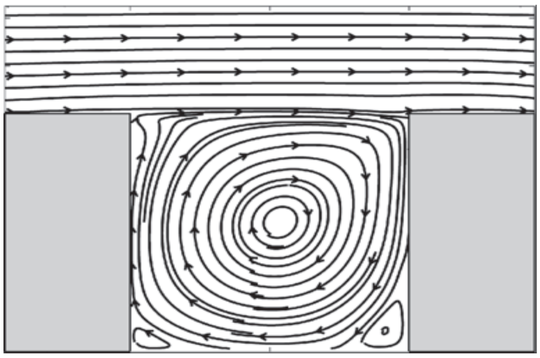

*Fig.2 Streamline field in the street canyon for $F_C$>0.8 (Kwak, 2012)*

Traffic emissions are the major outdoor source of directly emitted pollutants in urban regions. Many authors (e.g. Sini et al.,1996, Baldauf et al.,2013, Carpentieri et al., 2012) pay attention to elevated air pollutant exposures and adverse human health effects for population living close to streets with heavy transport traffic. It is especially crucial in densely-built and high-traffic areas in street canyons. Street canyons are not infinitely long or isolated entities in cities, but they are often segmented and connected to other canyons at urban intersections. High pollution levels are often associated with street canyons.

The street canyon factor $Fc$ is the ratio of the average height of buildings delimiting the canyon at the length $L$>2.5$H_B$ to the total width $W$ of the street.

$$F_C=H_{Bav}/W \tag{1}$$

Depending on the value of the ratio $Fc$, three types of airflow perpendicular to the canyon symmetry axis can be classified (Ahmad et al., 2005; Oke, 1988):

- skimming flow for $F_C$>0.8, which is characterized by a significant reduction of air exchange inside the canyon, Fig. 2 (Kwak et al., 2012)
- wake interference flow for $F_C$=0.20-0.8, where the stream is circulated inside the canyon and part of pollution is transported to adjacent canyons (mainly within the wake region)
- isolated roughness flow for $F_C$<0.20, when the influence of reciprocal interaction of the canyon walls on the interference can be ignored.

The value of $F_C$ has a decisive influence on diffusion conditions of pollution from traffic sources, but also from adjacent low stationary sources (Bagieński, 2006; Chang Cheng-Hsin, Meroney, 2003). When the street canyon factor $Fc$>0.8, high concentration of traffic pollutants can also occur on level of the upper storeys of a building delimiting the canyon (Park et al., 2004, Kwak et al., 2012).

The aim of the paper is to determine the influence of traffic emissions on indoor air quality especially in urban areas of compact settlement and intensive vehicle traffic in street canyons. The assessment is based on two streets with different urban structures in Poznań, a Polish city with over 500 000 inhabitants. For these roadways, concentrations of basic traffic pollution were specified, measurements were taken to determine concentrations of selected substances close to the streets and to ventilation air supplied to adjacent buildings and areas with increased pollution concentrations were identified. Fig. 3 and Fig. 4 show pictures of the analysed streets.

*Fig. 3 Street G – street canyon*

*Fig. 4 Street P – four-line street*

## 2 VEHICLE EMISSIONS

Total emission from road transport is the sum of exhaust emissions, evaporative emissions and road vehicle tire and brake wear emissions. Exhaust emissions include hot and cold-start emissions.

$$E_{Total} = E_{Hot} + E_{Cold} + E_{Ev} \tag{2}$$

Hot emissions depend on the kind and amount of fuel burned and the kind and age of an engine, i.e. motion velocity and a vehicle's technical data such as the category of a vehicle (passenger cars, light- and heavy-duty vehicles, buses), engine capacity, the kind of fuel, time of certification (permissible emission according to EURO standards). Cold-start emissions concern emissions of monoxide and hydrocarbons during the initial stage of the (cold) motion of a vehicle and depend on air temperature. In calculations they are treated as additional emissions considered solely for urban traffic. Evaporation emissions stem from fuel evaporating from a hot engine, carburettor and fuel tank. They are considered for fuel engine cars and depend on air temperature, humidity and fuel tank pressure related to these values. Vehicle emissions include pollutants such as CO, NO, $NO_2$, $PM_{2.5}$, $PM_{10}$, $CO_2$, VOCs including mono- and polycyclic aromatic hydrocarbons (MAH, PAH) and benzene $C_6H_6$, and to $CH_4$, $N_2O$, metals like Cd, Cr, Cu, Ni. Values of emission indexes for particular categories of vehicles in road transport are specified in the EMEP/EEA air pollutant emission inventory guidebook (European Environment Agency, 2009).

In recent years particular attention has been paid to PM emission. Fine particles $PM_{2.5}$ (diameter ≤2.5μm) and ultra fine particles (diameter ≤0.1μm ) emissions in urban regions are mainly emitted by diesel vehicles (Kim, Y. et al., 2011). Directly emitted elemental carbon soot (black carbon) from diesel vehicles, re-suspended dust from roads, and secondary acidic particles are major contributors of PM in urban roadside areas. The problem is particularly serious in cities with a large proportion of diesel-powered vehicles, e.g. Barcelona – about 50% (Schembari et al., 2013). According to the Air quality in Europe –report (2013), between 2009 and 2011, up to 96% of city dwellers were exposed to fine particulate matter ($PM_{2.5}$) concentrations above WHO guidelines.

Emission values may be referred to the linear dimension $E_{ti}$ (mg km$^{-1}$ s$^{-1}$) or the surface as traffic emission strength of a particular area with the i-th substance $E_{tia}$ (mg m$^{-2}$ s$^{-1}$). Traffic emission strength values were determined for selected pollutants based on real conditions of two streets in Poznan.

Street structure and car traffic variations:

- Street G – a one-way traffic (two-line) street with the traffic volume of 1600 vehicles per hour (v/h), passenger traffic with a 10% share of light-duty trucks, value of factor: $F_c$ >0.8 – street canyon
- Street P – a four-line street with the traffic volume of 3800 v/h, passenger traffic with a 15% share of light-duty trucks, value of factor: $F_c$ <0.2
- Vehicle traffic volume was averaged for the time interval from 7 a.m. to 7 p.m.
- Time intervals for which calculations were made:
  - Summer period: averaging Poznan climatic conditions for June, July, August; $t$=18.0°C, $\varphi$=45%.
  - Winter period: averaging climatic conditions for December, January, February; $t$=0.5°C, $\varphi$=90%

Tables 1 and 2 show emission values of particular pollutants for summer and winter periods for the analyzed streets.

Table 1 Values of substance emission and heat emission for summer.

| **street** | **vehicles** | **CO** | **NMVOC** | **$NO_x$** | **$PM_{2.5}$** | **benzene** | **$CO_2$** | **$Q_{dL}$** |
|---|---|---|---|---|---|---|---|---|
| | v/h | mg km$^{-1}$s$^{-1}$ | | | | | g km$^{-1}$s$^{-1}$ | kW km$^{-1}$ |
| G | 1600 | 2876.1 | 382.8 | 296.7 | 16.7 | 18.0 | 108.0 | 1594 |
| P | 3800 | 4921.2 | 643.4 | 760.6 | 35.2 | 30.8 | 209.2 | 3090 |

Table 2 Values of substance emission and heat emission for winter.

| **street** | **vehicles** | **CO** | **NMVOC** | **$NO_x$** | **$PM_{2.5}$** | **benzene** | **$CO_2$** | **$Q_{dL}$** |
|---|---|---|---|---|---|---|---|---|
| | v/h | mg km$^{-1}$s$^{-1}$ | | | | | g km$^{-1}$s$^{-1}$ | kW km$^{-1}$ |
| G | 1600 | 5212.2 | 560.2 | 320.0 | 25.7 | 29.1 | 119.4 | 1762 |
| P | 3800 | 8965.8 | 1158.6 | 782.6 | 53.0 | 52.0 | 231.4 | 3416 |

A higher value of the average traffic speed and a lower share of cold emission in street P in relation to street G contribute to lower values of CO, NMVOC and $C_6H_6$ emissions with higher values of NOx emissions. However, in winter emission of incomplete combustion products (CO, NMVOC, benzene) is much higher compared to summer, which results from an increase in fuel consumption, but first of all from an increase in cold emission indexes at a low air temperature.

The quantity $Q_{dL}$ determines heat flux emitted by vehicles as one of the components that generate the urban heat island (UHI). The values are relatively high. In summer as solar radiation flux density in the UV-VIS range is higher, additional significant anthropogenic heat emission has a considerable impact on chemical reactions that create secondary air pollution. For example, Taha (Taha, 1996) states that an increase in the Los Angeles local air temperature from 22$^o$C to 32$^o$C caused a rise in ozone concentration from 0.120 ppm to 0.240 ppm. Such a situation takes place especially in narrow street canyons, or areas with limited ventilation conditions, a low *SVF* (sky view factor) value and high radiation absorption values.

## 3 INFLUENCE OF A STREET'S STRUCTURE ON VENTILATION AIR QUALITY

### 3.1 Influence of a street's structure on pollution concentrations close to the street

A street's urban structure, often to a greater degree than traffic volumes, contributes to the level of its nuisance defined as concentrations of polluted air – both external (close to the ground) and internal air of the adjacent buildings. An experimental indicator of how a street's structure contributes to its nuisance is the ratio of pollution concentrations measured directly close to the street to the calculated value of the emission of the pollution *C/E* .

CO concentrations were measured for two streets: street G and street P in the meteorological conditions of summer and winter. The values were measured using the non-dispersive infrared method with a detection limit of 50 ppb. CO analyzers were located approximately 2 m from the street edge at the level of about 2 m, i.e. where the emission source directly affects people. Measurements were taken on working days between 10 a.m. and 12 noon (moderate traffic volume) and 4 p.m. and 6 p.m. (large traffic volume). Wind velocity did not exceed 1 m/s. Measured CO concentration values $C_{CO}$ were referred to CO emissions $E_{CO}$ calculated according to COPERT IV procedure. Tables 3 and 4 present the meteorological conditions of the measurements, traffic volume *N*, share of light- and heavy-duty trucks (LDT, HDT), the results of measuring the concentrations of $C_{COb}$ and computational analysis of the results comprising the concentration value of CO after deducting the background of $C_{CO}$, the calculated emission value of CO, the value of the ratio $C_{CO}/E_{CO}$ for particular measurements.

Table 3 CO concentration measurements and analysis of the results – street G

| **Temp.** C | **Humid.** % | **Time** hours | ***N*** v/h | **LDT** % | $C_{COb}$ μg m$^{-3}$ | $C_{CO}$ μg m$^{-3}$ | $E_{CO}$ μg m$^{-1}$ s$^{-1}$ | $C_{CO}/E_{CO}$ s m$^{-2}$ |
|---|---|---|---|---|---|---|---|---|
| 21.5 | 42 | 10-12 | 1310 | 8 | 1400 | 1250 | 2355 | 0.53 |
| 26.5 | 34 | 4-6 p.m | 1870 | 10 | 2100 | 1950 | 3361 | 0.58 |
| 20.0 | 42 | 10-12 | 1230 | 7 | 1100 | 950 | 2005 | 0.47 |
| 23.5 | 38 | 4-6 p.m | 1690 | 12 | 2300 | 2150 | 3190 | 0.67 |
| 1.2 | 85 | 10-12 | 1405 | 10 | 2550 | 2300 | 4577 | 0.50 |
| -0.5 | 90 | 4-6 p.m | 1780 | 9 | 3500 | 3250 | 5799 | 0.56 |
| 2.5 | 78 | 10-12 | 1520 | 6 | 2270 | 2020 | 4120 | 0.49 |
| 0.5 | 85 | 4-6 p.m | 1730 | 8 | 3450 | 3200 | 5520 | 0.58 |
| | | | | | | | average | 0.55 |

Table 4. CO concentration measurements and analysis of the results – street P

| **Temp.** C | **Humid.** % | **Time** hours | ***N*** v/h | **L/H-DT** % | ***C*$_{COb}$** μg m$^{-3}$ | ***C*$_{CO}$** μg m$^{-3}$ | ***E*$_{CO}$** μg m$^{-1}$ s$^{-1}$ | ***C*$_{CO}$/*E*$_{CO}$** s m$^{-2}$ |
|---|---|---|---|---|---|---|---|---|
| 20.5 | 40 | 10-12 | 2850 | 18 | 600 | 500 | 4132 | 0.12 |
| 22.0 | 41 | 4-6 p.m | 3920 | 15 | 740 | 640 | 4938 | 0.13 |
| 21.5 | 38 | 10-12 | 2950 | 13 | 450 | 350 | 3835 | 0.09 |
| 23.5 | 35 | 4-6 p.m | 4020 | 14 | 600 | 740 | 4928 | 0.15 |
| 2.4 | 85 | 10-12 | 3050 | 15 | 800 | 700 | 6405 | 0.11 |
| -0.5 | 90 | 4-6 p.m | 3840 | 12 | 1400 | 1250 | 7680 | 0.16 |
| 1.5 | 88 | 10-12 | 2710 | 14 | 880 | 730 | 6070 | 0.12 |
| -2.0 | 92 | 4-6 p.m | 3350 | 20 | 1200 | 1050 | 8207 | 0.13 |
| | | | | | | | average | 0.13 |

The canyon structure of street G causes emitted traffic pollution to accumulate within the canyon (Fig. 2), which is indicated by the high value of $(C_{CO}/E_{CO})av$=0.55 being over four times higher than that for street P. Such a structure of the street contributes to the fact that meteorological factors such as wind velocity and direction, temperature and solar radiation have a greater influence on average concentrations of particular pollutants and on vertical profiles of concentrations (Kwak et al., 2012; Park et al., 2004; Ahmad et al., 2005; Liu et al. 2003; Gartmann et al., 2012).

## 3.2 Influence of a street structure on pollution concentration values of ventilation air supplied to buildings

Two buildings were examined – one in street canyon G (Fig. 3) and the other in street P (Fig. 4). The one in street G has natural ventilation by opening windows and fan coil units. A measurement sensor was positioned outside a window at the level of 4.5 m above the street on its western side. The building in street P has a HVAC system. The air intakes were located on the roof of the building at the height of 17 m above the street and at the horizontal distance of 22 m from the edge of the street on its western side. A measurement sensor was placed in an air intake duct. Based on Gartman's research programme concerning the contribution of traffic emissions to air quality (Gartman et al., 2012), $CO_2$ concentrations were accepted as a traffic pollution indicator. Measurements were taken continuously for a fortnight from in June, 2014. On Sunday and Monday the wind blew with the speed of 2.0-3.5 m/s from the west, i.e. perpendicular to the axes of both streets. On the other days wind velocity did not exceed 1.2 m/s, which means that it did not have a substantial impact on traffic emission dispersion, especially within the street canyon.

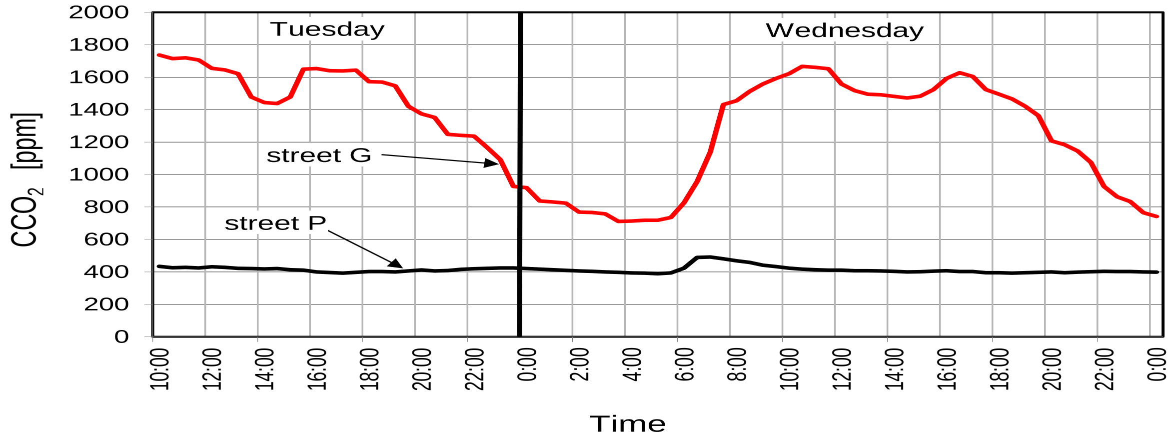


Fig. 5 $CO_2$ concentration values at the positions in streets G and P on Tuesday and Wednesday in June, wind velocity $u$<1.2 m/s

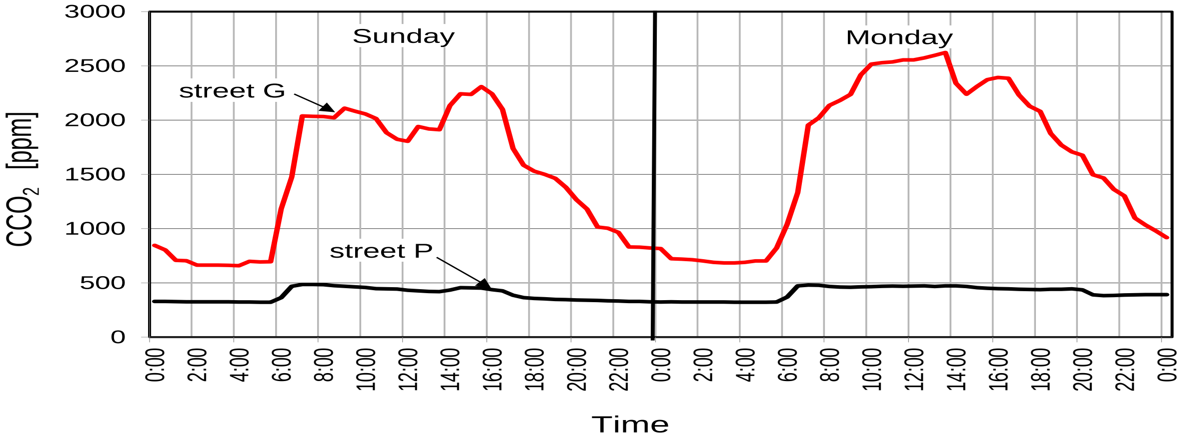


Fig. 6 $CO_2$ concentration values at the positions in streets G and P on Sunday and Monday in June, wind velocity $u$=2-3 m/s

Fig. 5 and Fig. 6 show $CO_2$ concentration values for selected days with low and higher wind velocities measured at positions close to streets G and P. Because of its placement concentrations at the position close to street P may be considered as those approaching the background concentration $C_{bac}$ for Poznań. Concentrations in street G were 3-5 times higher (up to 2600 ppm), especially on days with increased wind velocity. With the wind blowing from the west the whole canyon was in the cavity recirculation region. The increased velocity of the wind blowing from the west contributed to a rise in $CO_2$ concentrations in the air intake on the roof of the building in street P, which is located in the wake region. Concentration values varied within 24 hours and for weekdays and weekends with the variations being higher for the street canyon.

In order to identify building surfaces that are particularly exposed to being infiltrated by traffic pollutants from roadways a series of model experiments were conducted in a wind tunnel. The wind tunnel used for testing the diffusion of gaseous pollutants emitted from the short-point and line sources was constructed at the Institute of Environmental Engineering, Poznan University of Technology, Poland. A sketch of the experiment set-up is shown in Fig. 7. Each time particular elements of the set-up and the measurement system are adapted to an accepted program of the investigation. The explanation of such set-ups can be found in papers by Bagienski (2008).

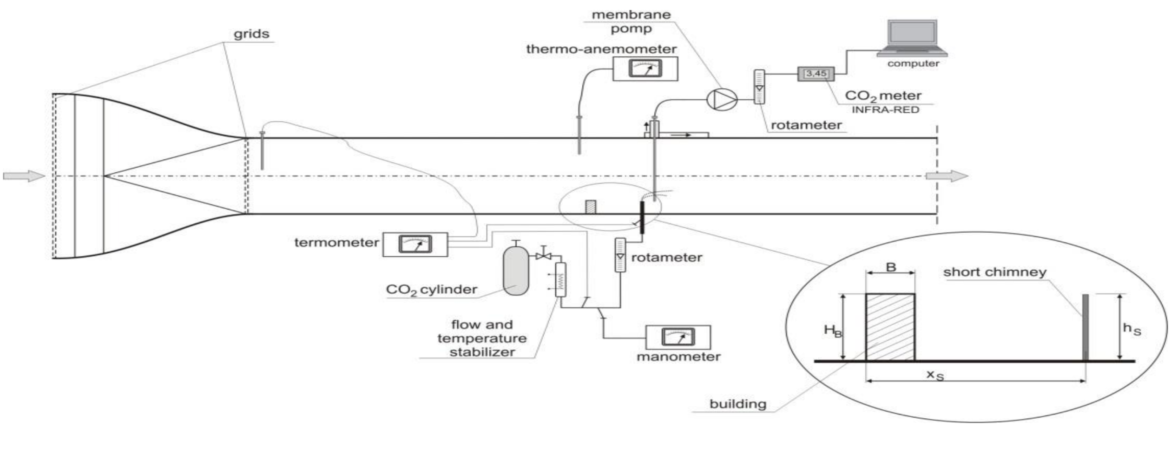


**Fig.7** A sketch of wind tunnel and experimental set-up (Bagienski, 2008)

A set of nozzles with horizontal vents for fume from the collector was used as a line source simulating traffic emissions. Figures 8 and 9 show a visualization of dispersion of fume emitted from line sources in the street canyon. Air flow with the velocity $u_H$=2 m/s was perpendicular to the axis of the street. The highest pollution concentrations were recorded at the leeward side of the building limiting the canyon from the windward side. Fumes were also identified close to the roof of the building, which means that pollution may enter an air intake even when they are on roofs. In the case of the canyon with the index $F_C$>0.8 high pollution concentrations may fill the whole of the canyon, which suggests that a considerable share of traffic emissions may enter buildings by means of natural or mechanical ventilation systems.

*Fig. 8 Line source of emission in the street canyon when $F_C$=1.0*

*Fig. 9 Line source of emission in the street canyon when $F_C$=0.3*

## 4 CONCLUSIONS

Traffic emission has a considerable impact on urban air quality. It may cause high concentrations of air pollution to appear especially in street canyons – much higher than in wide and open roadways. Building solids cause disturbances in wind flow by generating the cavity recirculation region and the wake region on the leeward side that limit the possibility of air pollution emitted in the areas being dispersed freely. This leads to higher concentrations of traffic emissions at different heights of the canyon, also on roofs. The pollutants may enter buildings by means of natural and mechanical ventilation systems. In a narrow street canyon pollution concentrations in an air ventilation intake of a building may be 3-5 times higher than in that located on the roof of a building in wide roadways. However, it needs to be taken into consideration that also in these cases traffic emissions contribute considerably to ventilation air quality. Before the location and the kind of ventilation air intake is designed for buildings, traffic pollution dispersion from adjacent roadways need to be analysed. This is particularly the case for buildings in street canyons.

## 5 REFERENCES


Ahmad K., Khare M., Chaudhry K.(2005). Wind tunnel simulation studies on dispersion at urban street canyons and intersections – a review. *J. of Wind Eng. and Ind. Aerodyn., 93*, 697-717

Bagieński Z. (2010). *The influence of structure of energy consumption on air quality in urban area in temperate climate*. Dissertation 440, Poznan University of Technology, Poland (in Polish with English abstract)

Bagieński Z. (2006). The analysis of dispersion of pollutants from short point sources – wind tunnel experimental investigation. *Environment Protection Engineering, 32*(4), 37-45

Bagieński Z. (2008). Analysis of diffusion within cavity region of pollutants from short-point sources – wind tunnel experimental investigation. *Environment Protection Engineering, 34* (4), 43-50

Baldauf, R.W., Heist, D., Isakov, V., Perry, S., Hagler, G., Kimbrough, S., Shores, R., Black, K., Brixey, L. (2013). Air quality variability near a highway in a complex urban environment. *Atmospheric Environment. 64*, 169-178.

Carpentieri, M., Hayden, P., Robin, A.G. (2012). Wind tunnel measurements of pollutant turbulent fluxes in urban intersections. *Atmospheric Environment. 46,* 669-674

Chang, C.H., Meroney R.N. (2003). Concentration and flow distributions in urban street canyons: wind tunnel and computational data. *J. of Wind Eng. and Ind. Aerodyn., 91*, 1141-1154

European Environment Agency (2009). Air pollutant emission inventory guidebook

European Environment Agency (2013). Air quality in Europe –report

Gartmann, A., Müller M.D., Parlow, E., Vogt, R. (2012). Evaluation of numerical simulations of $CO_2$ transport in a city block with field measurements. *Environ. Fluid Mech.,12*, 185-200

Jensen, S. S., Larson, T., Deepti, K.C., Kaufman, J.D. (2009). Modeling traffic air pollution in street canyons in New York City for intra-urban exposure assessment in the US Multi-Ethnic, Study of atherosclerosis and air pollution. *Atmospheric Environment, 43,* 4544–4556

Kim, Y., Gudmann, J.M. (2011). Impact of traffic flows and wind directions on the pollution concentrations in Seoul, Korea, *Atmospheric Environment*, *45*, 2803-2810

Kwak, K.H., Baik, J.J. (2012). A CFD modeling study of the impacts of $NO_x$ and VOC emissions on reactive pollutant dispersion in and above a street canyon. *Atmospheric Environment*, *46*, 71-80

Liu, H., Liang, B., Zhu, F., Zhang, B., Sang, J. (2003). A Laboratory Model for the Flow in Urban Street Canyons Induced by Bottom Heating. *Advances in Atmospheric Sciences, 20(4*), 554-564

Meroney, R.N., Pavageau, M., Radalidis, S., Schatzmann, M. (1996). Study of line source characteristics for 2-D physical modeling of pollutant dispersion in street canyons. *J. of Wind Eng. and Ind. Aerodyn., 62*, 37-56

Oke, T.R. (1988). Street design and urban canopy layer climate. *Energy Buildings*, *11*, 103-113

Park S.K., Kim S.D., Lee H. (2004). Dispersion characteristics of vehicle emission in an urban street canyon. *Science of the Total Environment, 323*, 263-271

Peterka, J.A., Meroney R.N., Kothari K.M. (1985). Wind flow patterns about buildings. *J. of Wind Eng. Ind. Aeroden., 21*, 21-38

Schembari, A., Triguero-Mas, M., de Nazelle, A., Dadvand, P., Vrijheid, M., Cirach, M., Martinez, D., Figueras, F., Querol, X., Basagana, X., Eeftens, M., Meliefste, K., Nieuwenhuijsen, M. (2013). Personal, indoor and outdoor air pollution levels among pregnant women. *Atmospheric Environment*, *64*, 287-295

Sini, J.F., Anquetin, S., Mestayer, P. (1996). Pollutant dispersion and thermal effects in urban street canyons. *Atmospheric Environment*, *30*, 2659-2677

Taha, H. (1996). Modeling the impacts of increased Urban vegetation on the ozone air quality in the south coast air basin. *Atmospheric Environment*, *30*, 3423-3433

Vincent, D., Annesi, I., Festy, B.,Lambrozo, J. (1997). Ventilation System, Indoor Air Quality, and Health Outcomes in Parisian Modern Office Workers. *Environmental Research, 75*,100-112