Dispersion from short-duration ground level point gas source in idealised urban canopy

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1. Introduction

Harmful gas leakages threaten life and health of city inhabitants. These gases can release from technological objects such as swimming pools, winter stadiums, cooling chambers or from chemical plants situated in city suburbs, for instance. Gas leakages in cities are a topic of interest in many studies. However, most of these studies deal with long-duration gas leakages (e.g. Kastner-Klein and Plate, 1999; Pavageau and Schatzmann, 1999), which are very rare in emergency situations. Hazardous gas leakages usually last less than one hour. Their dispersion differs from the long-duration leakages as their leakage duration belongs to the turbulent part of the atmospheric spectrum. The situation that will occur in the city after a short-duration leakage (called puff) is only one of many possible. Therefore, we have to conduct many replicas of the leakage under the same mean conditions to obtain a statistically representative dataset. This problem can be studied using the method of physical modelling in wind tunnels conducting a multiplied experiment repetition under the same experiment setting. In this paper, we focus on short-duration gas leakages from a ground level point source in an idealised city inner part.

2. Methodology

The experiments are conducted in the Laboratory of Environmental Aerodynamics of the Institute of Thermomechanics, Academy of Sciences of the Czech Republic. This laboratory possesses an open low speed wind tunnel with cross-dimensions 1.5 m × 1.5 m specialised in the boundary layer modelling (see Fig. 1). The boundary layer with neutral stratification is modelled with help of spires and roughness elements within the 20.5 m long development section situated in front of the 2 m long test section where models are placed (see Fig. 2). It is similar to the boundary layer found in cities according to VDI (2000).

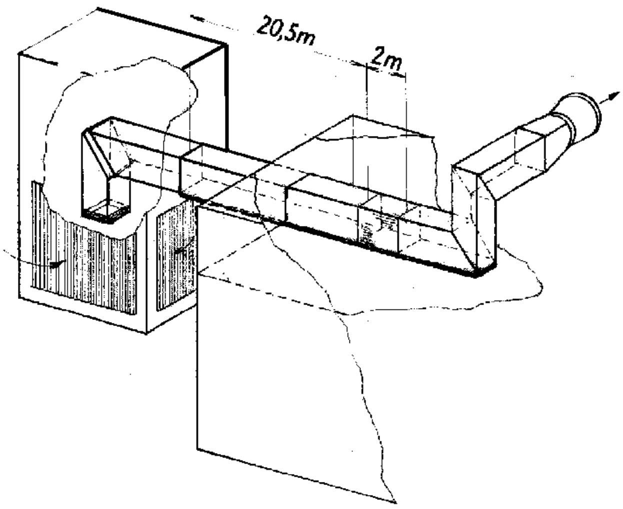

Fig. 1. Scheme of the wind tunnel.

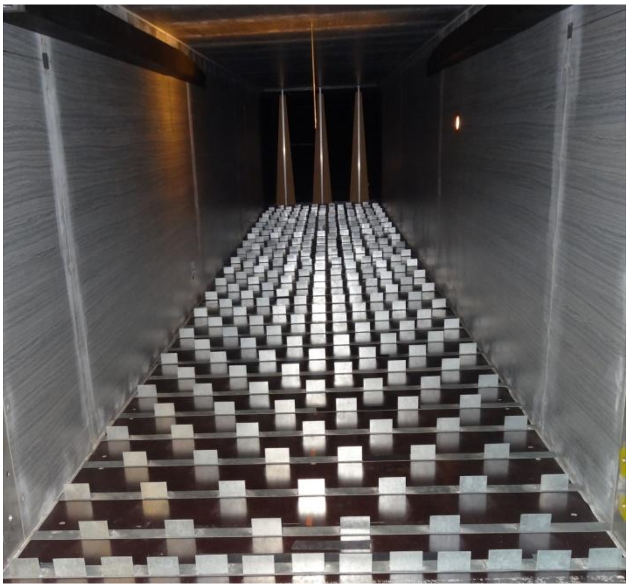

Fig. 2. Modelling of the boundary layer in the wind tunnel.

We use a model manufactured in the scale 1 : 400. The model represents idealised inner parts of European cities. It consists of 63 mm high buildings with pitched roofs organized into courtyards that are placed in equidistant spaces from each other (see Fig. 3).

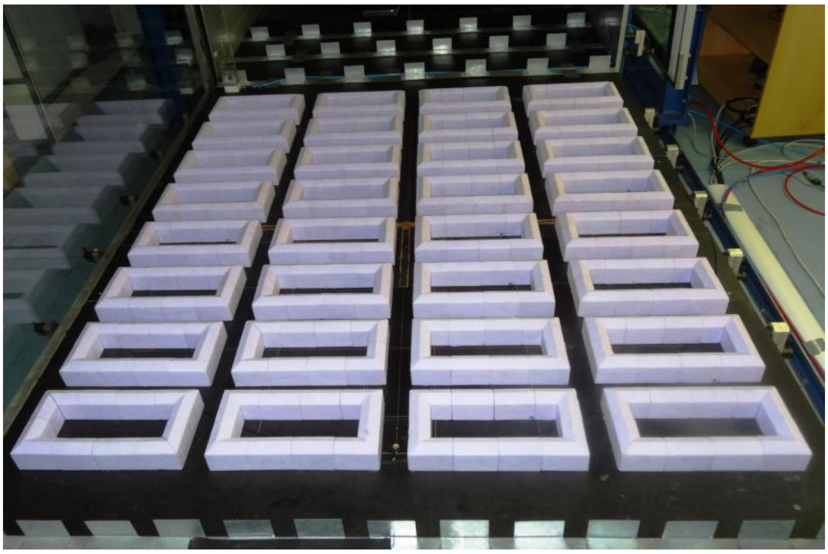

Fig. 3. Model of an idealised urban canopy.

The ground level point gas source is simulated by a short pipe with 8 mm in diameter. Its one end empties into the model ground. The other end is fixed into the electromagnetic valve orifice. The *3/2 electromagnetic valve of NORGREN* generates gas releases of a specified time duration. This process is operated by the timer relay *Programmable Logic Controller Siemens LOGO!* (see Chaloupecká et al., 2014a for more details). The duration of the gas release in the experiments presented in this paper is 1 s in the model scale (a little less than 7 minutes in the reality).

The gas clouds are detected by the *Fast-Response-Flame-Ionisation-Detector HFR400 of Cambustion Ltd.* (FFID). The FFID end of capillary, which sucks in a mixture of air and the passive contaminant ethane, is fixed within the human breathing zone.

The measured concentration time series are dimensionlessed. The dimensionless concentration for the point source is defined by the relation

$$C^* = \frac{CU_{ref}H^2}{Q}.$$

The tests of this dimensionless concentration values independence on the Reynolds number and on the source intensity were conducted to set the appropriate experimental conditions. Moreover, we use the dimensionless time

$$t^* = \frac{tU_{ref}}{H}$$

in this paper. In these relations U_{ref} stands for the reference speed (correspondents to the free atmosphere), H the characteristic height (in this experiment buildings height) and Q is the source intensity.

After that, each experiment replica of the dataset has to be analyzed. This analysis requires defining gas cloud characteristics measured at places contaminated by the gas release. The characteristic definitions differ in the literature from author to author. Generally we can find two main approaches - based on a threshold value (e.g. Harms et al., 2011) and a dosage (e.g. Zhou and Hanna, 2007).

Most studies apply the first - threshold - method. In this paper, we also define the puff characteristics using the threshold criterion. According to this criterion, the moment when the gas cloud attaches the sampler place is defined as the first time of the threshold value exceeding since the gas cloud is released. Unfortunately this definition faces difficulties in laboratory datasets. The reason is an undesirable sucking a dust particle into the detector during measurements. This situation can be seen in the measured concentration time series as a rapid increase of the measured value and its remaining there for only a very short time. These peaks known as spikes are false identified as a gas cloud entry to the sampler place by this algorithms. The solution to this problem offered Doran et al. (2007). According to this paper, the exceeding of the threshold value has to be detected in the time series not only once but within a whole specific period to identify the gas cloud arrival. But this redefinition combats a problem with the intermittency of the datasets. Recorded concentration time series fluctuate very much, huge concentration values are separated by the almost zero once within the presence of the cloud at the sampler place. As a consequence the puff arrival may be delayed in comparison with the reality or the whole gas cloud may not be even registered by the algorithms. Therefore we modified the method. We demand a detecting of the values over the threshold not in the whole specific period but only in a fixed number of values within the specified interval. Concretely we required the detection of the value above the threshold in the first value (tested value of arrival time) and in at least 50 % values from the 100 ms recorded concentration time series in the model scale since the tested arrival time (included the tested arrival time). This definition enables to register gas clouds in the intermittent signals. Moreover, it solves the problem with the spikes as only a few values within the recorded concentration time series are influenced by them and this phenomenon is recorded only once for a long time. As spikes can appear not only before the cloud arrives to the sampler place, we applied the same algorithms also to identify the time when the gas cloud leaves the sampler place – leaving time.

We also have to set a concrete threshold value into the algorithms. We wanted this value to characterize the maximum background concentrations at each sampler place. The background concentrations characteristics are estimated from the recorded concentration time series from all replicas at each sampler place. From each concentration time series, we use only the section after the gas cloud departure (the last few seconds). If we calculated the maximum value from these sections, this value could be influenced by the spikes. To prevent this, we use the 99 % percentile of the background concentration instead. We calculate the 99 % percentile of the background concentration from each replica at the sampler place and choose the maximum one from these values. To conclude, the threshold value is then set to the maximum of the 99 % percentile of the background concentration from all about 400 replicas at each sampler place.

Besides the arrival and leaving (departure) time of the cloud from the measurement position, we define the characteristic called dosage. Dosage is the total amount of concentration that strikes the measurement place during the gas cloud presence at it. Moreover, we define the peak concentration as the maximum concentration detected during the gas cloud presence at the sampler place.

The short-duration gas releases are influenced by turbulent wind. If we conduct the experiment once, we can only see one possible scenario from many that can occur after a toxic gas leakage. Therefore, we have to conduct many experiments under the same experimental set-up. The number of experiments determines the uncertainty of the characteristics statistic values. We conducted about 400 replicas at each sampler place. That determines the maximum uncertainty of the mean arrival time to 3 %, the mean leaving time to 5 %, the mean dosage to 6 %, the mean peak concentration to 7 %. The maximum is counted from the uncertainty of repetitive measurements of 400 replicas at a few measurement positions.

3. Results

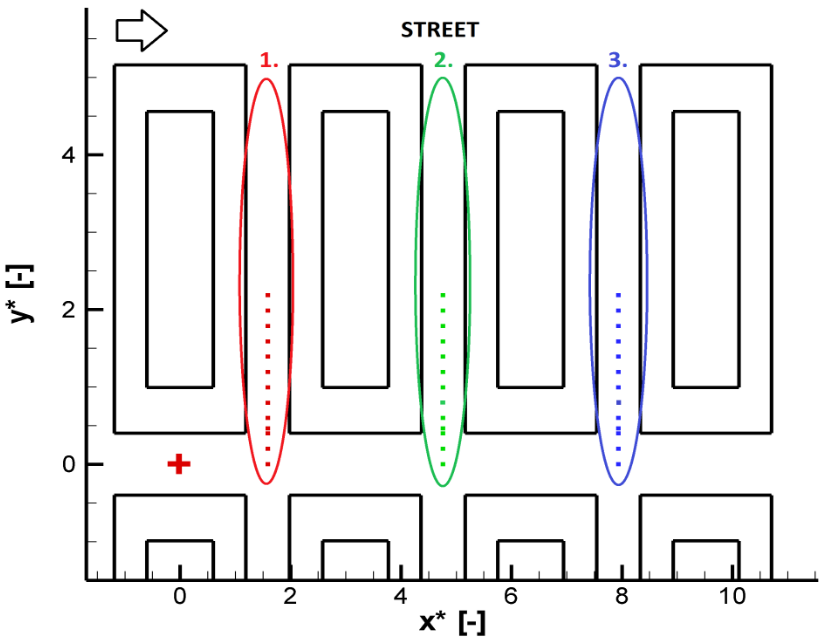

Fig. 4. Scheme of investigated section.

In this paper, we discuss the results from the data measured within the three streets transverse to the street where the ground level point gas source was placed (see Fig. 4). The positions where the measurements took place are depicted by coloured squares in Fig. 4. The cross represents the gas source position. The arrow marks the flow direction.

We show the mean value from the dataset of each place from the investigated model section in this paper. Moreover, we portray the box plots to graphically depiction of the datasets at each sampler position. To be able to display the results of one puff characteristic from all three streets in the one figure, we use the shifted box plots. The shift means that each three box plots of different colour (for the 1., 2. and 3. street) plotted next to themselves form one group. And this group relates to the one same y* position at the graph. In the box plots the median value (depicted by a square), 25 % - 75 % percentile (by the box) and the non-outlier range (by the whiskers) are graphically represented. The outliers are defined as the values above (bellow) the 75 % percentile (25 % percentile) of the dataset plus 1.5 multiply of the difference between the 75 % and 25 % percentile.

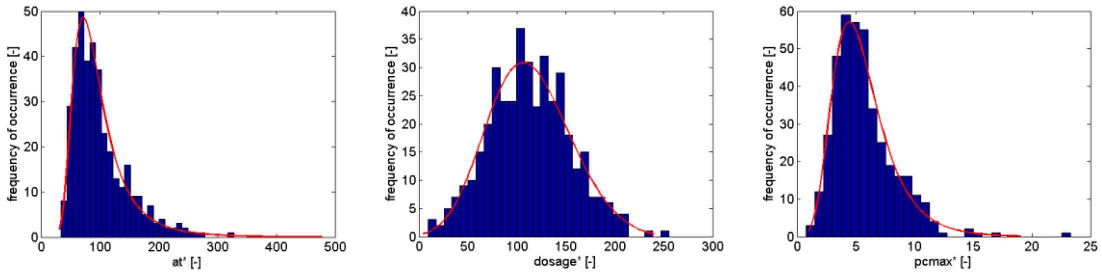

Fig. 5. Histograms fitted with Generalized extreme value distribution.

The graph in Fig. 6 presents data relating to the dimensionless arrival time. The results of median and mean values from datasets point to an increase of arrival time with the increasing distance from the street where the source is placed. But this trend also contains fluctuating values. This trend can be seen in all three transverse streets. The interquartile range seems to increase its value with the growing distance from the street with the source. However, the trend contains a few deviations, especially in the first street. The range, the value based on the extreme values, also seems to have an increasing tendency with the growing distance from the street with the source in the second and the third street but contains a few fluctuating values. The increasing trend is not apparent from the results in the first street. The datasets can be fitted with the Generalized extreme value distribution in all measurement positions except four as this hypothesis is not rejected according to the Chi-square-goodness-of-fit test with alpha = 5 %.

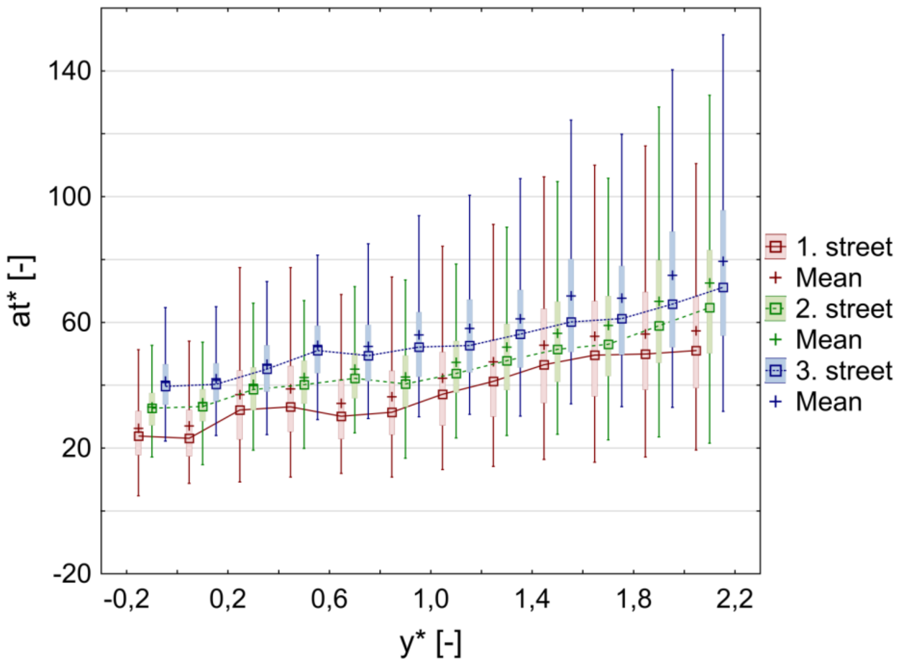

Fig. 6. Dimensionless arrival time.

In Fig. 7 results relating to the dimensionless leaving time from all measurement positions are depicted. Decrease of tracer gas can be described only with difficulty as the gas cloud is likely to be substantially discontinuous shortly before leaving the sampler place. Therefore, the leaving time seems to have usually wider range in comparison with the arrival time in the same measurement positions. The mean value (median) does not seem to increase its value with the increasing distance from the street with the source.

The total sum of concentration the sampler place is exposed - dosage - is displayed in Fig. 8. This value is highly important for emergency services. It can help to estimate medical consequences of people that were exposed of the gas release. Mean value (median) seems to descend with increasing distance from the middle of the street with the source in all three transverse streets but with a few exceptions. The same trend, and also with a few fluctuations (especially in the first transverse street), can be seen in the interquartile range values and the range. As well as for the arrival time the Generalized extreme value distribution seems to be the appropriate probability distribution for the datasets in most measurement positions as this hypothesis is not rejected according to the Chi-square-goodness-of-fit test with alpha = 5 %. It is rejected only in one position in the first street and in three positions in the third street.

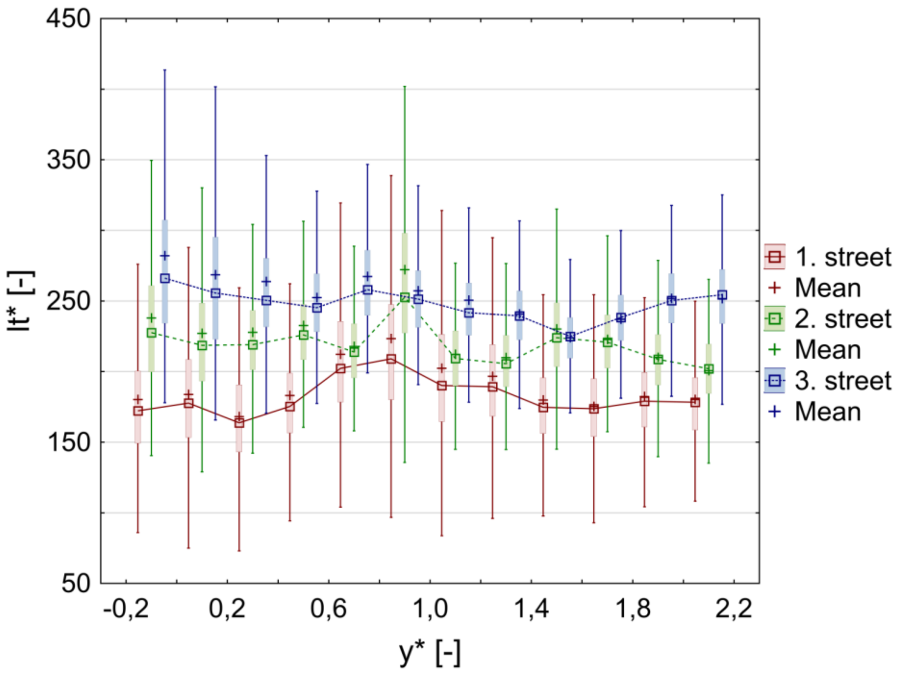

Fig. 7. Dimensionless leaving time.

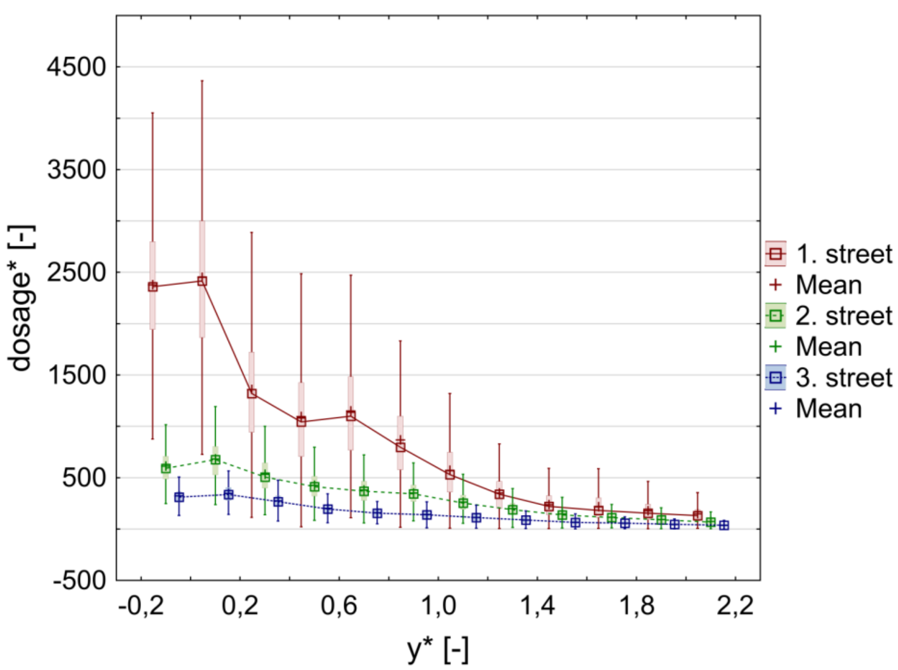

Fig. 8. Dimensionless dosage.

Results relating to peak concentrations are depicted in Fig. 9. The knowledge of maximum concentrations is one of the characteristics usually used to assessment of toxic gas releases hazardousness in crisis situations. However, Zimmerman et al. (1995) warned that this knowledge should not be overestimated as it depends on the measurement equipment resolution. Moreover, the FFID capillary, which sucks in the contaminant, is very thin. Therefore, it is very sensitive to the choking up (Chaloupecká et al., 2014b). The inner surface area of the capillary may be covered with an impurity and thereby reduce the capillary diameter a little during measurements. This leads to the measurement of a little lower values. As the maximum concentration is the only one value measured within the long time series, it is highly sensitive to this phenomenon. Therefore, the peak concentrations are sometimes also defined as the 99 % or the 95 % percentile of concentration from the time interval when the gas cloud is at the sampler place. But this value then substantially depends on the length of this interval from which the percentiles are calculated. Its length is determined by the definitions of the arrival and the leaving time. But these are usually defined differently from author to author. The mean as well as the median peak concentration seems to decrease its value with the increasing distance from the street with the source in all three transverse streets with a few measurement places exceptions. The datasets can be fitted with the Generalized extreme value distribution in all cases in the third street. In the second street there are two positions where the hypothesis of the Generalized extreme value distribution is rejected by the Chi-square-goodness-of-fit test with alpha = 5 %. In the first street this hypothesis is rejected even at four positions.

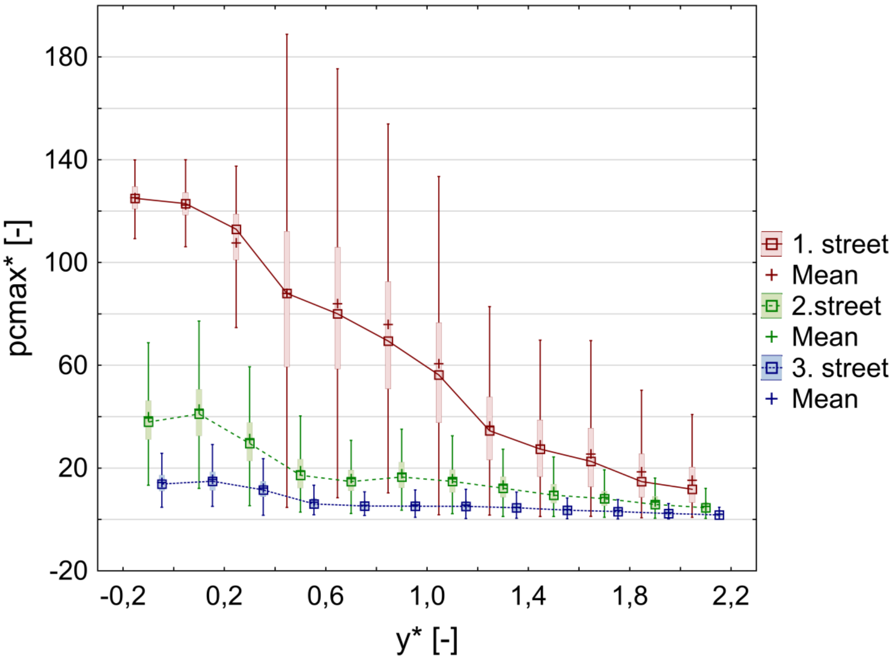

Fig. 9. Dimensionless peak concentration.

4. Conclusions

The datasets of the dimensionless arrival time, dosage and peak concentration can be fitted with the Generalized extreme value distribution in most measurement positions as this hypothesis is not rejected according to the Chi-square-goodness-of-fit test with alpha = 5 %. The median, the mean value and the interquartile range of the dimensionless arrival time seems to increase its value with increasing distance from the street with the source but this trend also contains fluctuating values. The dimensionless arrival time range also seems to have the increasing tendency with the increasing distance from the street with the source in the second and the third street. The dimensionless leaving time seems to have usually wider range of values in comparison with the dimensionless arrival time in the same measurement positions. The mean value (median) of the dimensionless leaving time does not seem to increase its value with the increasing distance from the street with the source. The mean value (the median, the interquartile range value and the range) of the dosage seems to descend with increasing distance from the middle of the street with the source in all three transverse streets but with a few fluctuations. The mean as well as the median dimensionless peak concentration seems to decrease its value with the increasing distance from the street with the source in all three transverse streets with a few position exceptions.

Acknowledgment

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