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Evaluation of a new method for puff arrival time as assessed through wind tunnel modelling

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ABSTRACT

Deliberate or accidental gas leakages threaten people's lives. Short-duration releases of gas are influenced by actual phase of turbulent atmospheric flow and therefore the study of these situations requires multiple repetitions of the leakage under the same mean conditions. Such a set of experiments was conducted in a wind tunnel on a scaled model of an idealized urban canopy created by rectangular buildings with pitched roofs organized into closed courtyards. Concentration time series of high time resolution were measured by a fast flame ionisation detector. The arrival time of gas from short-duration discharges was investigated at a few places of detection. This paper introduces a new method of defining gas arrival time, one not only applicable in the post-processing analysis but also in the operative stage. Moreover, it shows the results of other commonly used gas arrival time definitions (visual and dosage methods and a method utilizing the maximum detected concentration). It was explored both, the change in the arrival time value in individual realisations and places as well as the change in statistical values calculated from ensembles (mean, median, quartiles). Furthermore, the dependence of the definitions of arrival time on their parameters is discussed.

1. Introduction

Air pollution studies are mainly concerned with long-term gas releases. Such releases are mostly releases from permanent sources of contaminants (e.g., smoke from factory stacks). But only a small number of studies examine short-term gas leaks. This scenario is predominant in emergency situations (e.g., chemical plant accidents), as suggested by Balczo et al. (2012). These gas leakages very often last less than one hour (e.g., the accident of the industrial facility working under the EU Seveso II Directive described in Baumann-Stanzer et al. (2015), the Bhopal disaster – Varma and Varma, 2005 – or Orica's Kooragang Island chemical plant accidents in August and November 2011 – e.g. Orica-Wikipedia (2017)). Their dispersion differs from long-term releases since their leakage duration falls into the turbulent part of the atmospheric spectrum (e.g., Van der Hoven, 1957). Under the same mean ambient and leakage conditions many different accident scenarios can occur (e.g., Zimmerman and Chatwin, 1995). This fact contributes to the difficulty of conducting research into short-term gas releases. Many leakage realisations under the same mean conditions are needed for risk assessment (e.g., Zimmerman and Chatwin, 1995; Chaloupeck& et al., 2016). In contrast to the dispersion from long-term gas sources, dispersion from short-term gas sources (puffs) computed by common emergency mathematical models (e.g., ALOHA – Jones et al., 2013; HotSpot – Homann and Aluzzi, 2014) is inaccurate (e.g., mean dosage is underestimated by about one order of magnitude), since these models are typically based on time-averaged or parametric equations, as discussed in Baumann-Stanzer et al. (2015). Moreover, according to Baumann-Stanzer et al. (2015), these simple models provide only few output variables for puffs. Baumann-Stanzer et al. (2015) also report that advanced computational fluid dynamics (CFD) models (e.g., large eddy simulations, LES) are capable of simulating the variability of individual puffs. On the other hand, these LES models need rigorous

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validation and they are very expensive computationally, as stated e.g. by Zhiyin (2015) as well as Baumann-Stanzer et al. (2015). In field campaigns, variable atmospheric conditions make the achievement of the same mean ambient conditions for long periods nearly impossible and puff ensemble size is very limited (e.g., Baumann-Stanzer et al., 2015). In laboratory experiments, the ambient as well as leakage conditions can be controlled and therefore the wind tunnel represents the suitable research tool for short-term gas releases.

In wind tunnel experiments, the time course of leakage is recorded by a concentration measurement device at different exposed places. As a result of these near-point measurements, concentration time series are obtained. Concentration time series are then analysed to obtain the puff characteristics. One such characteristic to describe the gas cloud is its arrival time to the place of detection. The puff arrival time represents an important factor in determining safe courses of action for inhabitants in exposed areas.

In a concentration time series, the recognition of puff arrival is aggravated mainly by the noise of the equipment utilized for concentration measurements, the residue of tracer gas as well as dust particles sucked into the detector. Therefore, cloud arrival time cannot be defined by the first detection of a non-zero concentration in the time series. Different researchers overcome these difficulties by utilizing various arrival time definitions. Some researchers do not find the first moment of gas arrival at the sampling place, but the time at which the maximum concentration is detected, referred to as travel time, instead (e.g., Zhou and Hanna, 2007). To find the first moment of gas presence at the sampling place, three main methods can be found in the literature. These methods are a visual method, a method utilizing a dosage and a method based on a threshold criterion. The visual method (e.g., Yee et al., 1998), which uses eyesight, has the advantage that a human is more capable, compared with an inflexible algorithm, in coming to a decision whether an increase in concentration is caused by a gas cloud or not. On the other hand, a degree of subjectivity arises via this approach to the analysis. In addition, the time demands of this approach make it impossible to analyse huge databases, but the visual method can serve as a comparison with results reached using the various automatic methods. The dosage method (e.g., Harms et al., 2011) uses 5% of the total dosage reached at the sampling place for the definition of arrival time. Harms et al. (2013) report that this definition enables puffs with different concentrations to have a uniform arrival time. The gas cloud arrival at the sampling place can also be defined by a threshold criterion. The choice of the threshold value changes widely from author to author. It can be classified into three main branches of approach. The first approach uses a value that is dependent on a specific released substance. The threshold is chosen according to the hazardousness of the gas, such as a lower flammability limit (e.g., Pontiggia et al., 2011). This method allows one to generate maps for emergency services with the affected zones highlighted according to their level of danger. The second approach is one in which the threshold value is dependent on the course of a recorded puff signal concentration. Zhou and Hanna (2007) chose the threshold value relative to the recorded maximum (peak) concentration. They determined the beginning of the puff as the time when the concentration exceeded a 10% maximum concentration. The third option is to look at the statistical characteristics of background noise. Doran et al. (2006) utilized a fixed threshold value, a quantity which was higher than the detectable minimum, as well as the residual values from a previous realisation for all sampling places. But these residual values are different for the places close to and distant from the gas source. A higher threshold chosen according to the residual values found close to the source may cause delayed puff arrival detection at places distant from the source. Therefore, this definition does not seem to be suitable for places very differently distanced from the source. This problem can be resolved by utilizing different thresholds at different places (e.g., Chaloupecká et al., 2016). Laboratory concentration time series are very often measured by a fast flame ionisation detector. The detector can suck in a dust particle, thereby causing a false registration of a few very high concentration values in the time series. Looking at only one value, while searching for arrival time within a time series, can lead to incorrect values. Doran et al. (2007) therefore require the detection of a value of at least the threshold quantity in a specific time interval instead of a single value. But this requirement is problematic because of the concentration time series intermittency. Chaloupeck& et al. (2016) therefore require the detection of values of at least the threshold quantity, not in the entire time interval, but in a specific percentage of cases instead.

Zhou and Hanna (2007) find the threshold of the realisation by looking at the whole concentration time series. But the cloud arrival could probably be better recognised if we look only at the behaviour of the beginning of the concentration time series. However, the problem is that we do not know at which time, after the gas discharge, the cloud arrives at the detection position and therefore, we cannot use this approach. Instead, we can utilize concentration time series registered before the cloud release. This is the central idea of the new method as presented in this paper. Moreover, we compare the results with other methods applied to the same dataset. This comparison is important, since widely different arrival time definitions lead to different results but no comparative study (as far as the authors know) exists.

In the paper, the experimental set-up and the data analysis is described in the section Materials and Methods. In this section, all the methods used for determining puff arrival time (visual method, threshold method utilizing residual concentration, dosage method, and threshold method utilizing the value of detected maximum concentration) are described. The Result section, which follows Materials and Methods, is divided into five subsections. The visual method is dealt with in the first subsection. The results of this method are then used as a comparative tool for the other three methods and are described in the subsequent three subsections. An overview of the results is presented in the final subsection. Finally, the major outcomes are covered in Section 4.

2. Materials and methods

2.1. *Experimental set-up*

The experiments were conducted in the Laboratory of Environmental Aerodynamics of the Institute of Thermomechanics. The laboratory possesses an open, low-speed wind tunnel specialised in boundary layer modelling, with cross-dimensions of 1.5 m × 1.5 m. The boundary layer is developed in a 20.5 m long section with the use of spires and roughness elements. A boundary layer in 1:400 scale with a neutral stratification was used in the experiments. The modelled boundary layer characteristics agree with the recommendations of VDI (2005) for flows found in cities (Grimmond and Oke, 1999; Britter and Hanna, 2003). The vertical profiles of the mean velocity and the intensity of turbulence of velocity component along the main wind direction at the inlet section are displayed in Fig. 1. In the section, a Prandtl probe used for velocity measurements was positioned at the wind tunnel centreline. Behind this section, the incoming flow comes to a test section, where measurements are conducted. To the bottom of the test section, model is fixed. A model of an idealised urban canopy, as found in European city centres (e.g., Heathcote, 2014) and modelled to 1:400 scale (Fig. 2), was used. It consisted of houses which were 63 mm high and 38 mm wide. The houses had pitched roofs. The height of the roofs constituted 13 mm from the height of houses. The houses were organised into 150 mm × 300 mm courtyards (outer dimensions) placed 50 mm from each other. A short-duration, ground-level point gas source with a circular orifice of 4 mm in radius was used in the experiments. The tracer gas discharges were generated by an electromagnetic valve operated by a timer relay. The duration of discharges for majority of the experiments was 1 s. For the experiments with different discharge durations, the duration changed from 0.5 s to 10 s. The constant flow rate within each puff release