Journal of Wind Engineering & Industrial Aerodynamics 179 (2018) 407–418

Contents lists available at ScienceDirect

Journal of Wind Engineering & Industrial Aerodynamics

journal homepage: www.elsevier.com/locate/jweia

# Estimation of local tracer gas concentration probability from minimum input data

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A R T I C L E I N F O

*Keywords:*
Air pollution
Atmospheric dispersion modelling
Emergency response
Field measurements
Statistical model

A B S T R A C T

Emergency response forces need to be prepared for making vitally important decisions in the possession of very few trustable information. Chemical plants using hazardous materials are usually monitored for accidental release, equipped with local wind sensor and some estimates are available for the potential source intensity. Concentration levels are expected to be forecasted from this minimum information in case of accident. Most fast response dispersion models rely on the Gaussian dispersion model, despite it being limited to small scale turbulence induced by surface shear. In this paper, data of multiple field experiments are brought to common platform and, based on the statistical investigation of this dataset, an atmospheric dispersion model is proposed, which allows for the reconstruction of the pointwise concentration statistics as functions of windward and lateral coordinates. The new statistical model may be used to predict the ground level concertation profile of given probability, with the limitations to near ground continuous sources localized on flat terrain at medium latitude. At least an order of magnitude higher lateral spread of the plume can be seen compared to standard Gaussian plumes and the profiles are tilted to the right reflecting the effects of large scale atmospheric turbulence and Coriolis effects.

## 1. Introduction

One of the world's worst industrial accidents was the Bhopal disaster in India in 1984, when over 500,000 people were exposed to toxic gases, mostly methyl isocyanate (Varadarajan et al. (1985)). This case is researched even after nearly 30 years by Havens et al. (2012) who revisited and questioned the accuracy of modelling used earlier. The possibility of nuclear power plant accidents is another great safety concern nowadays. Airborne radionuclides can travel great distances, therefore these problems should be investigated in a continental or global scale. One of the great nuclear accidents was the Chernobyl power plant disaster in 1986. Pudykiewicz (1988) investigated the dispersion of radionuclides with a hemispherical numerical model and showed that radionuclides travelled a long distance across continents during the first few days after the release. The dispersion of radionuclides released by the Fukushima Dai-ichi reactor disaster in 2011 was also investigated by many researches, e.g. by Huh et al. (2013) and Hu et al. (2014). A comprehensive survey of airborne radionuclide dispersion models was carried out by Leelőssy et al. (2018).

There are various approaches to model atmospheric dispersion of gaseous materials. Holmes and Morawska (2006) give a thorough review about different modelling approaches and available software. The review focuses on dispersion of particulate matter, although most models are also suitable for investigating gaseous dispersion. A total of 29 software are reviewed including box models, Gaussian models, Lagrangian models and computational fluid dynamics (CFD) software. Van Leuken et al. (2016) recently reviewed the available modelling techniques with special attention on bioaerosol dispersion. They reviewed 19 different software including Gaussian, Lagrangian and Eulerian (CFD) models. Both reviews agree in that the choice of approach depend heavily on circumstances, i.e. complexity of terrain, scale of the problem (local, regional, global), desired accuracy, available time and computational resources, etc.

For operative risk assessment the most widely used models are based on the Gaussian plume model or the Lagrangian approach. A non-extensive list of Gaussian based software used in different countries is: ADMS (Carruthers et al. (1994)) and AERMOD (Hanna et al. (2001)), ALOHA (Jones et al. (2013)), OPS-ST (Van Jaarsveld et al. (2012)), SCREEN3 (EPA (1995)). Lagrangian models in use are: CALPUFF (Scire et al. (2000)), DERMA (Sørensen et al. (2007)), HYSPLIT (Draxler et al. (2016)), RIMPUFF (Thykier-Nielsen et al. (1999)). The Gaussian plume based models have the lowest computational resource demand, as only

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https://doi.org/10.1016/j.jweia.2018.06.015
Received 5 February 2018; Received in revised form 14 May 2018; Accepted 22 June 2018
Available online 5 July 2018
0167-6105/

an analytical expression has to be evaluated, thus this approach is considered to be suitable for supporting fast decisions in emergency situations. Although, the extensive changes of wind direction in atmospheric boundary layer both due to the interaction with the Ekman layer and the presence of large scale vertical vorticity are not taken into account in every Gaussian plume based model (e.g. ALOHA), resulting in gross underestimation of the lateral dispersion intensity. The same holds for wind tunnel testing compared to field measurements. Robins (2003) concluded that lateral spread of the plume can be higher in case of field measurements in contrast to wind tunnel measurements.

In the past, mostly between the years 1950 and 1990, numerous field measurements have been performed regarding dispersion over rural terrain. The main reason behind these experiments was to have sufficient knowledge about dispersion of hazardous gases resulting from nuclear/bio weapons. The first well documented action was the Round Hill experiment conducted in 1954/55 and 1957 (Cramer et al. (1958)). Several measurement campaigns were carried out in the following decades, e.g. the Green glow experiment in 1959 documented by Fuquay et al. (1964), the Hanford 64 experiment in 1964 (Nickola et al. (1983)), the Hanford 67 experiment between 1967 and 1969 published by Nickola (1977) and Droppo (1985), the Cabauw tracer experiment in 1977–78 (Agterberg et al. (1983)). The valuable observations from the referenced field experiments are not yet processed to their full potential. These data can provide more realistic scenarios compared to wind tunnel measurements as they incorporate the natural fluctuation of wind speed and wind direction due to larger meteorological scales.

It is assumed in this paper, that the averages of wind intensity and wind direction are known, furthermore the source can be regarded as a steady near ground source of given location and intensity. Emergency response forces typically need to work with such instantly accessible data. What can be stated about the concentration field if only that much information is available? We attempt to answer this question by developing a statistical model on the basis of experimental observations of several measuring campaigns.

## 2. Material and methods

### 2.1. The datasets

In this section the details of the measurement datasets referenced in section 1 are introduced. The most important parameters – stack height, measurement arcs, azimuthal resolution of measurement points, tracer gas used and number of usable data – are summarized in Table 1. All the measurements were carried out over rural terrain. Data were downloaded from www.harmo.org/jsirwin.

The Cabauw experiment was carried out in Cabauw, Netherlands (51°58′N, 4°56′E). The plume was emitted from an elevated source from a meteorological mast at a height of 80 and 200 m. The tracer gas used was Sulfur-Hexafluoride ($SF_6$). Measurements were made at ground level

**Table 1**
The identifier of experiment, stack height ($H$), distance from the source ($R$), angular resolution ($\Delta\vartheta$), tracer substance (gas or aerosol), and the number of usable concentration measurements.

| Experiment ID | $H$ [m] | $R$ [km] | $\Delta\vartheta$[°] | Tracer substance | No. of data |
|---|---|---|---|---|---|
| Cabauw | 80 and 200 | around 4 | around 1.5 | $SF_6$ | 619 |
| Green glow | 2.5 to 5.5 | 0.2 to 25.6 | 1–2 | ZnS | 5110 |
| Hanford 64 | 56 and 111 | 0.2 to 25.6 | 1–2 | ZnS | 1166 |
| Hanford 67 | 1 to 111 | 0.2 to 25.6 | 1–2 | ZnS, Kr-85, Rhodamine-B, Fluorescein | 10529 |
| Prairie Grass | 0.46 and 1.5 | 0.05 to 0.8 | 1–2 | $SO_2$ | 7466 |

(1.5 m) along one measurement line which ran along the road around the mast at a distance of approximately 4 km. The area is considered topographically flat inside a radius of around 20 km from the source. The field contains meadows and trees, the roughness height of the area was determined by Wieringa (1976) by taking into account the vegetation patterns. The average quantities such as wind velocity, wind direction and temperature correspond to 30 min of averaging time. Some turbulence characteristics such as fluctuation of wind speed, wind direction and temperature, Reynolds stresses and heat fluxes were also measured and calculated. When determining the concentration data, the background concentration was subtracted (Driedonks et al. (1978)).

The other three experiments (Green glow, Hanford 64, Hanford 67) were carried out at the same location, the Hanford Reservation in Southeast Washington. The Green glow experiment was carried out in the summer of 1959, the Hanford 64 in 1964 and the Hanford 67 experiments were carried out between 1967 and 1969. The Green glow experiment is meant to be the extension of the Prairie Grass experiment. In Prairie Grass experiment measurement points were only considered up to 800 m downwind distance. The Green glow measurements were extended to 25.6 km downwind of the source. The stack height was considered to be near ground (2.5–5.5 m) and measurements were taken at a height of 1.5 m. The terrain is said to be slightly rolling in the downwind direction, the drop in height is around a total of 90 m along 25.6 km. Most of the drop is localized between 6.4 km and 9.6 km. The terrain was the same in case of Hanford 64 and 67 and also the measuring arcs (up to 25.6 km). Stack heights of 56 m and 111 m were used in case of Hanford 64 and between 1 and 111 m for Hanford 67. Zinc-sulfide (ZnS) was used as tracer material in all three experiments, but for Hanford 67 additional measurements were made with tracers of Fluorescein (Uranine), Rhodamine-B and Krypton-85. The emission time in case of Green glow and Hanford 67 was 30 min (with slight deviations in the minority of the cases) and varied between 20 and 72 min in case of Hanford 64 (resulting in an average of 43 min). In the dataset only those measurements are recorded for which the travel time was sufficient to generate statistically correct concentration data, therefore 0 concentration values due to insufficient travel time do not skew the mean and deviation calculations.

In Figs. 1 and 2 the measurement sites of the detailed measurement actions can be seen. Although the maps represent the 2017 state, still it can be considered relevant to the flat rural experimental site.

Additionally, the Prairie Grass (Barad (1958)) experiment was also used for testing the capabilities of the present model. As mentioned before, during this campaign only short range dispersion was investigated up to 800 m, therefore it is not for full validation, but to show the short range predictive ability of the model. The measurement site was approximately 8 km northeast of O'Neill, Nebraska (42.49°N, 98.57°W).

It can be seen in Table 1 that more than 24000 individual concentration data has been processed in the present investigation. As Prairie Grass experiment is only used for short range predictive comparison, in the following sections only Cabauw, Green glow and the Hanford 64/67 series are considered. These experiments still contain more than 17000 concentration measurement data resulting from 121 measurement series.

The model is intended to describe the parameters of pointwise statistical distribution of concentration at any surface point downwind from the source, provided that the source location, intensity, wind direction and wind speed are given. Only near ground release (max. 5.5 m) data is used for statistics (i.e. data of Green glow and part of Hanford 67) and the data relevant to elevated sources are used for checking and exploring the effects of the source height. In many emergency situations the atmospheric stability parameter and the surface roughness height can only be estimated or guessed for a first response, therefore they are treated as stochastic parameters. The present investigation is limited to flat terrain at medium latitude and neutral to extremely stable meteorological conditions, because the experimental observations correspond to such conditions. The stability classes of the 121 measurement series (Prairie Grass experiments not included) can be seen in Fig. 3. The stability classes are