CHEMICAL ENGINEERING TRANSACTIONS

VOL. 43, 2015

A publication of
AIDIC
The Italian Association
of Chemical Engineering
Online at www.aidic.it/cet

Chief Editors: Sauro Pierucci, Jiří J. Klemeš
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ISBN 978-88-95608-34-1; **ISSN** 2283-9216

DOI: 10.3303/CET1543416

Experimental Investigation on Concentration Profiles and Fluctuations of Dense Gases in Wind Tunnel

Mauro Gaggero[a], Andrea P. Reverberi[b], Bruno Fabiano*[,a]

[a] DICCA - Department of Civil, Chemical and Environmental Engineering - Polytechnic School - Genoa University, via Opera Pia 15, 16145 Genova (ITALY)
[b] DCCI - Department of Chemistry and Industrial Chemistry – Genoa University, via Dodecaneso 31, 16146 Genova (ITALY)
brown@unige.it

One of the most frequent accident scenario following a loss of containment during HazMat transportation or processing is represented by the dispersion of a dense gas release. Several dispersion models are available to this purpose, more or less rigorously accounting for gravity slumping, air entrainment and possible heat transfer. Under confined geometry, the correct evaluation of possible concentration fluctuations represent an up-to-date research topic, both considering the process sector and a peculiar application represented by operating theaters for surgery. In this last context, the use of heavier than air gas is usually performed for anaesthetic application, while few validation data are available on the dispersion behavior following a fugitive emission and exposure of persons inside the enclosure. On these bases, the experimental phase of this paper was performed in a laboratory-scale wind tunnel of circular section, under different Reynolds number regimes, considering a continuous release scenario of two tracer gases, namely carbon dioxide and sulphur hexafluoride, at different low release rates. A detailed study on concentration fluctuations and time series is presented yielding reliable information on the influence of the different source types and flow rates. Conclusions are drawn on practical feasibility and application of the experimental results, in view of safe optimization of the design and mode of operation of ventilation systems in the considered settings.

1. Introduction

A thorough statistical analysis of historical data taken from the MHIDAS database (“Major Hazard Incident Data Service”) performed by Planas-Cuchi et al. (1997) evidenced that among 6099 accidents occurred up to the end of 1993 the highest percentage (52.15%) corresponded to release, followed by fire (41.52%). The results were confirmed by analysis of accidents in the downstream oil industry from the early 1930 s to 2010 evidencing an upward trend in term of frequency in the last thirty years, with the exception of the last five-year period, with the highest percentage of entries corresponding to Plant/process (64.8%) items and connected to a “loss of containment” (Fabiano and Currò, 2012). Accidental releases of hazardous heavy gases lead generally to the formation of creeping clouds subjected to low dilution processes, especially under stable atmospheric conditions. The problem of concentration accumulation in an enclosure connected to a release of a non neutral behavior gas and to the evaluation of the maximum allowable build-up (Palazzi at al.,2013) is of practical interest in industrial processes, room ventilation and safety assessment. Furthermore, the interest is related to the fact that an economically feasible solution to by-pass densely populated urban areas, or topographic obstacles is to lay gas pipelines, possibly together with water conducts, in tunnel or galleries, so that the problem of HazMat pipeline risk assessment still requires further theoretical insights into the estimation of failure frequency (Milazzo et al., 2010) and into the calculation of the consequences depending upon the interaction with the environment and the dispersion, or build-up in semi-confined regions (Palazzi et al., 2014). Additionally, very few data are available on the possibility of mimicking a tunnel fire at the laboratory scale, with reference to both thermal profile and combustion products behaviour (Vianello et al., 2012). The dispersion of chemicals in an embedding stream subject to a random or deterministic velocity profile has long been object of intense investigations for its basic implications in pollution control (Bagatin et al., 2014), in

Please cite this article as: Gaggero M., Reverberi A., Fabiano B., 2015, Experimental investigation on concentration profiles and fluctuations of dense gases in wind tunnel, Chemical Engineering Transactions, 43, 2491-2496 DOI: 10.3303/CET1543416

environmental safeguard and connected possible side-on effects on safety (Fabiano et al.,2014). In the specific context of gas advection, the prediction of pollutant concentration at the ground level on areas surrounding factories (Vairo et al., 2014) and the corresponding inverse problem of source identification (Reverberi et al., 2013) for known concentration values on the ground, or in the lower troposphere are still open problems concerning industrial chemistry and chemical engineering communities. An accurate modelling of gas jets is required in combustion technology (Kang et al., 2015) where great efforts are devoted to circumvent some drawbacks related to instabilities of the solution of coupled momentum and transport equations in the presence of terms related to the intrinsically stochastic character of motion. For this reason, new algorithmic techniques have been tested and implemented in the design of combustion engines, where gas dynamics optimization plays a primary role in the minimization of waste gases preserving high performances in terms of specific power. An accurate analysis of experimental data is required not only for validating the models describing the heavy gas dispersion, but also for improving the basic understanding of the physical phenomena and related scaling problems. From an experimental point of view, many studies have been devoted to the statistical analysis of time series pertaining to concentration fluctuations of pollutants whose diffusion is subject to natural or artificial obstacles and meteorological cycles. Santos et al. (2011) investigated the dispersion of propylene released between building blocks under unstable atmospheric conditions. The influence of mechanical and natural ventilation were ruled out both for indoor and outdoor mean and peak concentrations. Other authors (Klein and Young, 2011) focused on concentration fluctuations of tracer gases mimicking the contaminants affecting urban air quality. They proposed a concentration statistics based on a clipped-gamma distribution for the concentration data that proved to be superior to previous model distributions adopted in literature. The paper of Van Ommen et al. (2011) contains a detailed survey of several approaches for time-series analysis of fluctuations in fluidized-bed reactors. Among these methods, the Hurst analysis is considered as a non-conventional technique extensively applied in many disciplines where the detection of short and long-range correlations between signals is required. In this study, we propose an approach to the analysis of signals for a tracer gas concentration in turbulent regime. This examination could reduce considerably the limits of uncertainty of the risk analysis and concentration prediction providing valuable information for the efficient design of ventilation systems or reliable verification of existing ones. The paper is divided as follows: in section 2, we describe the experimental apparatus and the relevant sampling procedure. In section 3, we outline the method where a concentration data set is mapped onto a one-dimensional correlated random walk of a fictitious particle. In section 4, we draw the conclusions and we trace the direction for future works.

2. Materials and methods

2.1 Experimental set-up

Experimental runs were performed utilizing the circular section wind tunnel schematized in Figure 1 and characterized by an inner diameter of 0.5 m and an overall length of 5.35 m. The tunnel consists of five different sections, namely air inlet, flow pre-homogeneization chamber, working chamber realized in transparent polymethyl metacrilate, second homogeneization chamber and air outlet suitable shaped and equipped with a helical suction fun (Dynair LM 250, Brescia, Italy) with adjustable speed in the range 0.3-10 ms^{-1}. The circular shape section and honeycomb airflow rectifiers located at the homogeneization chambers ensured an excellent flow homogeneity inside the tunnel, minimizing the formation of whirlwinds, as well as stagnation phenomena connected to edge presence.

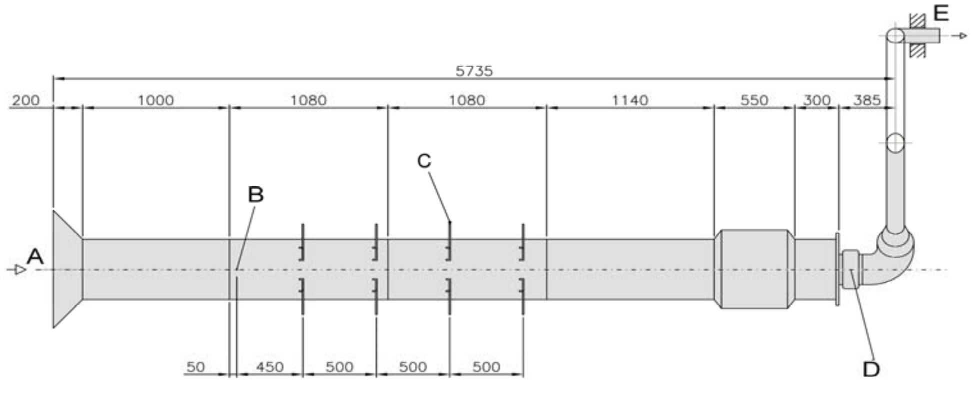

Figure 1: Laboratory scale wind tunnel (A = air flow inlet with honeycomb rectifier; B = tracer gas source; C = sampling points; D = suction electrical fun; E = air flow exit).

Air speed was measured by an anemometer with a 16 mm helical probe (Testo S.p.A., Milan, Italy). The circular shape section and honeycomb airflow rectifiers located at the entrance of the homogeneization chamber ensured an excellent flow homogeneity inside the tunnel, minimizing the formation of whirlwinds, as well as stagnation phenomena connected to edge presence. Air sampling and tracer gas dosing were performed utilizing a Multipoint sampler and doser Monitor Type 1302 (Brüel & Kjær, Denmark) based on photo-acoustic spectroscopy (PAS) with a detection limit of 10^{-3} ppm. The doser system has six outlet channels allowing the attainment of the selected gas tracer flow rate, as continuous or discontinuous dose. The sampler system has six inlet channels: four channels were utilized as measuring points at different lengths of the tunnel, one channel at the inlet and the last one at the exit, in order to verify the overall mass balance. Steady-state conditions were attained with release duration of 60 min. At steady-state conditions following sampling points were considered: S1 and S2 respectively 1 m and 1.5 m downwind the release source point. The tracer gases were supplied utilizing three different nozzles corresponding to nominal release rates of 0.5, 3.0 and 15.0 mL/s, at absolute pressure ranging from 300 to 450 kPa, so as to minimize errors connected to deviations from isokinetic conditions.

2.2 Tracer gases

We utilized as tracer gases carbon dioxide and sulphur hexafluoride. The former was selected considering that transport of CO_2 in bulk, by pipeline from point sources, or by ship is an up-to-date activity related to Carbon Capture and Storage (CCS) and can produce emerging risks, as carbon dioxide is characterized by IDLH (Immediately Dangerous to Life or Health) value of 40,000 ppm (Vianello et al., 2013). Also in this sense, hazards related to new technologies associated with CCS represent an upcoming challenge to process safety research (De Rademaeker et al., 2014). During experimental runs, the value of ambient carbon dioxide inside the wind tunnel was subtracted to the recorded one. The latter, sulphur hexafluoride, is a colorless, odorless and incombustible gas which can be used as tracer in the field of ventilation efficiency in buildings and indoor enclosures and environmental quality monitoring (Tsai, 2007). SF_6 is characterized by a Threshold Limit Value (TLV) equal to 1000 ppm (ACGIH, 2002). Its molecular weight 146.07 is rather similar gas such as halothane, enflurane and isoflurane, commonly used for induction and maintenance of general anesthesia in mixture, at percentages ranging from 0.5 to 5 %, with nitrogen protoxide and oxygen.

3. The data analysis

As an example, Figure 2 clearly evidences how the spreading and dispersion of a dense gase is characterized primarily by the value of its negative buoyancy.

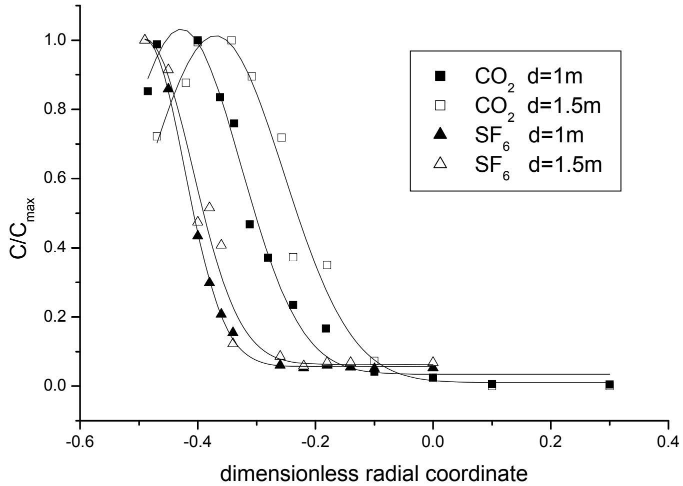

Figure 2: Plot of the normalized concentration versus the dimensionless radial coordinate of the channel. Squares and triangles refer to carbon dioxide and sulphur hexafluoride, respectively. Solid and open symbols refer to sampling points located at 1.0 and 1.5 m from the injection point along the axis. All data were collected for a wind speed of 0.4 m/s. Solid lines are Gaussian interpolations of the four data sets.

As the source is a continuous one, the concentration builds up until reaching the steady-state with a trend consistent in both cases with the hydrodynamics of a dense gas, in terms of vertical slumping down. In the seminal paper of Peng et al., (1992), the authors were the first who proposed a mapping between a sequence of nucleotides in a DNA chain and a sequence of steps in a trajectory of a random walker. The statistical properties of the so-called "DNA-walk" allowed them to detect the presence of correlations between nucleotides along the DNA structure. An analogous approach was successfully adopted in econophysics and it proved to be an useful tool in the analysis of price fluctuations (Scalas, 1998). We think it is worth recalling some essential aspects of this method, as it represents the theoretical basis of this section. In Figure 3, the SF_6 concentrations measured at the detection point S1 have been collected for fixed increments of time t. Hence, C_i is the concentration value at time $i\Delta t$. These values have been mapped onto a one-dimensional random walk defining an integer variable u that assumes the values +1 or -1 according to the following rules:

a) if $C_{i+1}>C_i$, set $u_i = +1$

b) if $C_{i+1}<C_i$, set $u_i = -1$

The position y_n a random walker at the n-th time step can be written as:

$$y_n = y(n\Delta t) = \sum_{i=1}^{i=n} u_i \tag{1}$$

In Figure 4, the trajectory of such a walker (that could be defined as a "concentration-walker" moving according to the concentration time-series reported in Figure 2) is visualized. The statistical properties of this motion can be analysed following a traditional approach based on the root mean square fluctuations $F(t)$ around the mean square displacement, namely:

$$F^2(n\Delta t) = \left\langle [\,\Delta y(n\Delta t) - \langle \Delta y(n\Delta t)\rangle\,]^2 \right\rangle = \langle \Delta y^2(n\Delta t)\rangle - \langle \Delta y(n\Delta t)\rangle^2 \tag{2}$$

where $\Delta y(n\Delta t)$ is defined as:

$$\Delta y(n\Delta t) = y[(n_0 + n)\Delta t] - y(n_0\Delta t) \tag{3}$$

and the symbol $<\cdots>$ means the expected value, averaged on the number of runs differing from one another in the starting value n_0. Each run comprises k contiguous data points. For a fixed Δt, we are interested in the scaling of $F(n)$, whose trend can be described as follows:

- if the concentration fluctuations are really random, $F(n)$ has a power-law dependence typical of an uncorrelated random walk, that is $F(n)\sim n^{1/2}$.
- if there are correlations between concentration values at different times, $F(n)$ still haves a power-law behaviour with $F(n)\sim n^{\alpha}$, $\alpha \neq 1/2$.

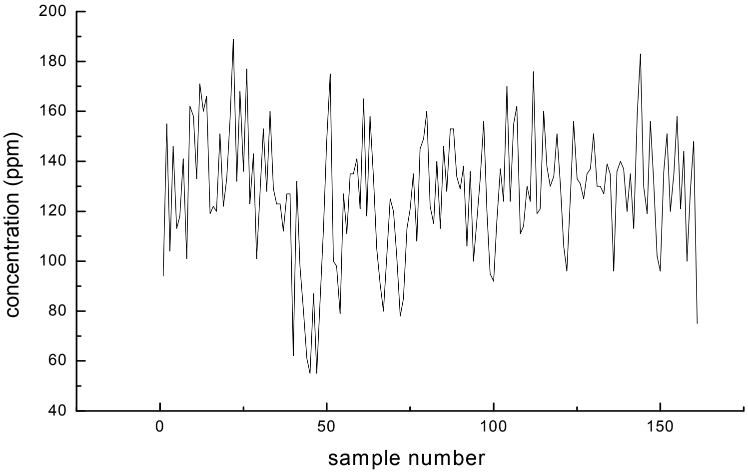

Figure 3: Plot of concentration values collected at the sampling point S1 located at a distance d = 1 m downwind the release source, versus time. The maximum sampling time gap is 25 seconds.

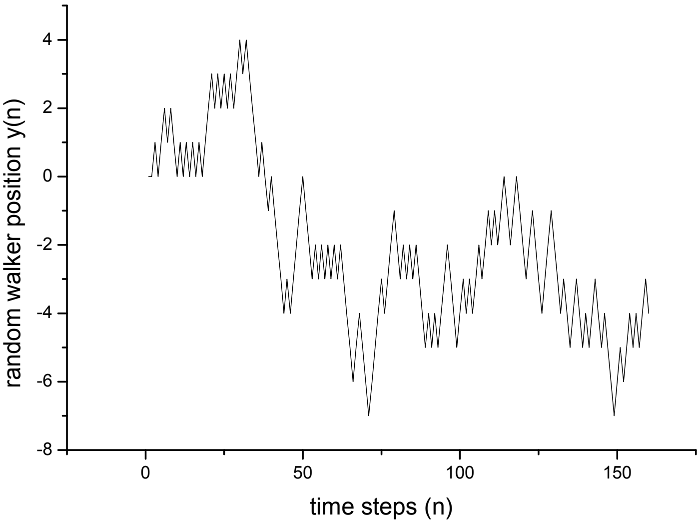

Figure 4: Plot of the random walker trajectory obtained by the concentration data reported in Figure 2.

In Figure 5, the trend of *F(n)* has been reported versus *n* in a double logarithmic plot and the average <···> has been drawn for three different runs. In fact, the larger is *k*, that is the time span of investigation, the smaller is the number of runs on which the average is calculated and the greater is the noise affecting the results. A linear interpolation of the scatter graphs have a slope $\alpha=0.36 \pm 0.015$ for $20<k<40$, a value far from the one corresponding to a genuine Brownian motion. This result cannot be solely explained by the presence of noise related to the limited number of concentration data points. Instead, it seems to be consistent with short-range correlated fluctuations in the concentrations being affected by an anti-persistent behaviour. This amounts to saying that a variation of concentration is statistically followed by a variation of opposite sign with a frequency higher than the one observable in a pure random process (Kristoufek, 2010). A possible origin of such a trend could be explained remembering that the jet of injected tracer gas is subject to pulsations and eddies whose frequency depends on the fluid dynamics of the bulk stream and on the role played by wall effects.

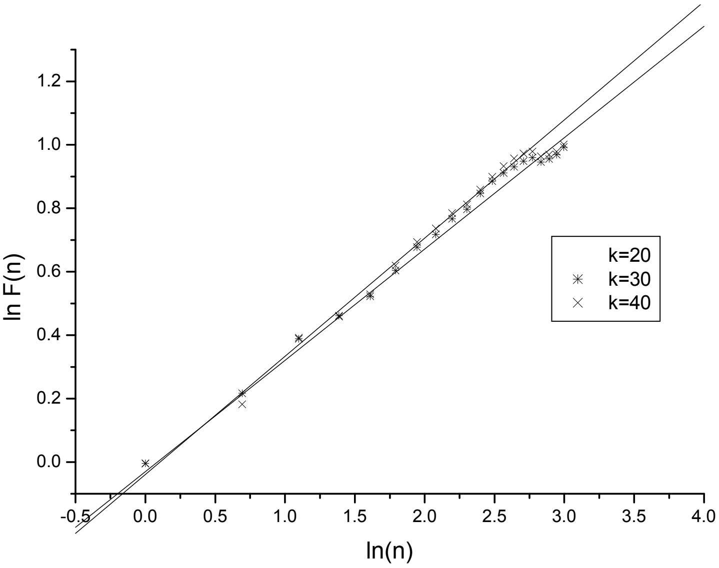

Figure 5: Double logarithmic plot of the root mean square fluctuation F(n) versus the time step n of the random walker trajectory for three different values of k. Upper and lower lines are data interpolations for k=20 and 40, respectively.

4. Conclusions

We propose an experimental study aiming at analysing the dispersion of a tracer gas in a turbulent gas stream flowing in a pipe. A bulk stream of air is generated by a fan operating downstream with the purpose of establishing a velocity profile constant in time inside the channel. A gas with density greater than the one of the flowing air is injected at different distances from the tube walls and it undergoes a convection/diffusion process giving a concentration profile whose fluctuations are recorded by suitable sensors. The concentration data are mapped onto a one-dimensional random walk and the statistical properties of the root mean square fluctuation function suggests the presence of short-range correlations in the time series of concentration values. This result is discussed in light of previous results concerning heavy gases dispersions in forced streams. This paper represents a step towards the goal of developing the understanding and modelling capabilities for dense gas releases by considering the case of confined geometry. Additionally, the cases are of interest in their own right, as they may apply directly to certain planned ventilation operations.

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