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Heavy gas dispersion by water spray curtains: A research methodology

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Abstract

The mitigation of the consequences of accidental releases of dangerous toxic and/or flammable cloud is a serious concern in the petro-chemical and gas industries. Nowadays, the water-curtain is recognized as a useful technique to mitigate a heavy gas cloud. The paper presents a research methodology, which has been established and undertaken to quantify the forced dispersion factor provided by a water-curtain with respect to its configuration.

The method involves medium-scale field tests, Wind-Gallery tests and numerical simulations. These different approaches are discussed and exemplified by typical results emphasizing the observed concentration reduction due to the water-curtain.

Keywords: Gas dispersion; Mitigation; Water spray curtains

1. Introduction

Industrial hazards and their mitigation are serious concerns in the petro-chemical and gas industries. Nowadays, the water-curtain is recognized as a useful technique to mitigate various types of industrial hazards. Its simplicity of use, efficiency and adaptability for different types of risks (gas dispersion, absorption, fire-attenuation) makes it an attractive tool.

In order to provide aid to design water-curtains for the chemical industry, an engineering code CASIMIRE has been developed as described by Hald, Dandrieux, Dusserre, and Buchlin (2003). With respect to the water-curtains configuration (type of nozzles, nozzle spacing, operating pressure, spray height) the code may evaluate the mitigation efficiency for the different applications stated above.

In the domain of gas releases, the CASIMIRE code predicts the dilution factor corresponding to the design of the water-curtain. Two databases are incorporated in the code: the nozzles, such that the spray hydro-dynamical part is described; and gases, the physical and chemical parameters are known. The CASIMIRE code has earlier been partly validated by laboratory tests carried out in the VKI Wind-Gallery by Griolet et al. (1995), Pretrel (1997) and St-Georges et al. (1992). Now, a complementary project is undertaken to provide a new database derived from field tests, additional Wind-Gallery tests and CFD simulations.

The mitigation of gas release consequences are described by the mechanical effect a water-curtain has on its environment by introducing air entrainment, the chemical absorption between the gas and the water, and finally the buoyancy effect by heat transfer. In this project, only the mechanical effect is considered.

The air entrainment performance of a spray has been already precisely assessed through very good agreement between dedicated Laser Phase Doppler measurements (Algieri, 2003; Pretrel, 1997; St-Georges et al., 1992), CASIMIRE predictions (McQuaid, 1975) correlation and CFD simulations (Lewtak, 2003).

Based on the three aforementioned approaches, this paper aims to provide some guidelines to estimate the dilution factor yielded by a water curtain with respect to the operating parameters and a comparison of the different approaches undertaken. This study leads to a correlation, which will be implemented in the CASIMIRE code.

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2. Field tests

The Buxton test series (Moodie, 1981), the Goldfish project (Blewitt, Yohn, Koopman, Brown, & Hague, 1987), and the Hawk experiments (Schatz & Koopman, 1990), which have involved carbon dioxide and hydrogen fluoride clouds, respectively, investigate the influence of the curtain operating and wind conditions on the curtain efficiency. They clearly point out the detrimental influence of the wind on the curtain efficacy and constitute a useful basis of comparison with the present field tests (not yet finished). This comparative exercise will be performed in a next future.

One of the objectives of the present study is also to examine if it could exist a scaling effect between the laboratory and the full-scale experiments. That is the reason why all the tests are performed with the same industrial nozzle design (at different scales), whose hydraulic characteristics have been determined in the VKI Water-Spray facility by Algieri (2003).

Three different campaigns of field tests have resulted in a characterisation of a gas cloud in interaction with a water-curtain and the subsequent concentration reduction. The two first campaigns have been conducted with chlorine gas releases at different flow rates. The third campaign, not yet completed, is based on carbon dioxide to get larger release rate with less safety requirement.

2.1. Experimental set-up

The field tests are conducted on a large flat terrain. The area including the source, the water-curtain and the measurement points is of the order of 100 m^2. For safety reasons, the experiments are controlled by safety services and a security area is defined during the trials.

Since the project focuses only on mechanical dispersion of heavy gas cloud the selected gases are chlorine (Cl_2) and carbon dioxide (CO_2), both characterised as heavy gases with low solubility in water.

The flow rate of the gas releases is ranging from 1 to 8 kg/min for chlorine and from 15 to 25 kg/min for carbon dioxide. The emission lasts about 10 min in which the tests consist of a free (without water-curtain) and forced dispersion (with operating water-curtain) measurements. The source is oriented horizontally close to the ground level.

The water-curtain consists of a pipeline equipped with a uniform distribution of pressure nozzles with a spacing of 20 cm. Industrial full cone nozzles are used, with an initial spray angle of 90°. The droplet size distribution has been measured by PDA in the VKI Water Spray Facility.

In the Cl_2 tests, the water-curtain is 5 m long and 2 m high, and the water flow-rate is of the order of 200 kg/min per curtain meter. For the CO_2 tests, the water-curtain is 10 m long as the source is much larger and the height is adjustable between 2 and 3 m. The actual water flow-rate does not exceed 100 kg/min per curtain meter.

The main concentration measurements are performed at 3.5 m downstream the water-curtain in the free and forced dispersion case. The gas sampling is performed 10 cm above the ground.

The chlorine concentration is measured trapping the Cl_2 in a soda solution by bubbling a mixture of air and Cl_2 in the solution. The concentrations are deduced by UV spectrophotometry.

In a similar way, the CO_2 concentration may be deduced by colorimetric method, trapping the CO_2 in a barium hydroxide solution. In addition, instantaneous measurements are also achieved using infrared probes.

The meteorological conditions are measured during the experiments by two different means, a vane propeller anemometer and an ultrasonic anemometer. The wind velocity and direction are measured at 2 and 10 m above the ground. The temperature and the relative humidity are also measured.

2.2. Experimental procedure

A test consists of a sequence of two experiments. The first experiment is the free dispersion during which no action is taken to reduce the cloud concentration; it represents the worst-case scenario. Fig. 1 displays a typical view of this test. To ensure as much as possible the same wind and release conditions, it is directly followed by the forced dispersion during which the water-curtain is acting. Fig. 2 presents a typical view of this test. This chronology

Fig. 1. Free dispersion field tests.

Fig. 2. Forced dispersion, field test, $R_M = 10.7$.

mimics exactly the procedure also adopted during the Wind-Gallery tests.

All the experiments are recorded by video camera such that the sequence of events can be visualized.

3. Wind-Gallery tests

A further parametrical study is conducted in the VKI Wind-Gallery for the facility of performing a systematic investigation on the water-curtain efficiency. Here, special emphasis is given to the effect of the ratio of the height of the water-curtain to the height of the gas cloud: such a parameter is not easy to be studied in the field tests.

The test section of the Wind-Gallery is sketched in Fig. 3. It is a rectangular channel 1 m high, 1.3 m wide and 7 m long. The airflow is produced by a battery of four ejectors mounted at the back end, thus producing a low pressure that keeps gas leaks towards the inside of the test section. The gallery has demonstrated very uniform velocity profiles and turbulence levels The wind speed in the Wind Gallery may vary from 0.25 to 1 m/s, which is equivalent to speeds ranging from 5 to ∼18 km/h at full scale. The Wind Gallery was constructed in compliance with material resistance requirements needed to use certain chemicals: the pollutant cloud is simulated by releases of SF_6, N_2 or CO_2. Upward and downward pointing curtains can be tested. Wind speed, pollutant source and water-curtain can be monitored. Concentrations and temperature can be measured, both in the gas and in the liquid.

The gas chosen for the investigation of the forced dispersion is CO_2. A grid in the bottom of the tunnel that covers the width of the tunnel assures a constant release flow in the lateral direction of the tunnel. At the source, the gas is pure and the concentration in this point is 100%. A gas flow meter measures constantly the mass-flow of the gas during an experiment and the typical release rate is of the order of 20 kg/h.

The water-curtain in the Wind-Gallery is equipped with the same type of nozzles as in the field tests at scale 1/4. The curtain spreads over all the width of the test section. In downward operating mode the nozzles may be located at 0.3, 0.4 and 0.5 m above the ground and their maximum number is 26 per meter. The floor of the test section is porous so that water is easily salvaged by a recirculation hydraulic system.

A hot sphere anemometer measures the wind-speed profiles upstream the curtain. The concentrations measurements are performed by means of a special hot wire technique developed by Colin and Olivari (1971) at the von

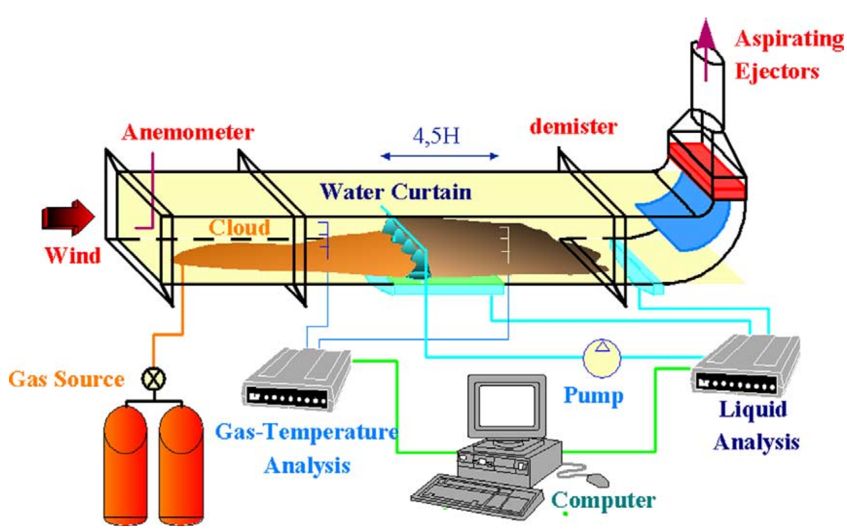


Fig. 3. Schematic of the VKI Wind-Gallery.

(a) R_M =2.0 (b) R_M =10

Fig. 4. Wind-Gallery visualizations.

Karman Institute and extended further on by Maroteaux, Maroteaux, and Murat (1991). A constant temperature hot wire is placed in a sonic hole in order to be insensitive to the flow-velocity. In this way, the signal of the hot wire depends only on the physical properties of the gas. Calibration procedure is needed. The gas sampling is made via vertical combs of 10 small tubes each, successively opened and closed by means of electro-valves connected to a vacuum pump. A rack of concentration probes is positioned 1 m downstream of the water-curtain. A dedicated program based on Test-Point software allows the PC control of the electro-valves and the data acquisition. At the present writing time, new tests are underway to compare this measuring technique with the instantaneous infrared captors used during field tests.

4. Numerical simulations

CFD simulation of forced dispersion of a heavy cloud by water spray curtain is performed with the code Fluent-®/UNS v. 6.1. The behavior of the gas phase is modeled by the averaged Navier-Stokes equations coupled to the RNG k-ε model for the turbulence. The continuous phase is considered as an incompressible fluid, comprising a mixture of an inert gas (ambient air) and vapor species. The experimental boundary conditions are accurately mimicked.

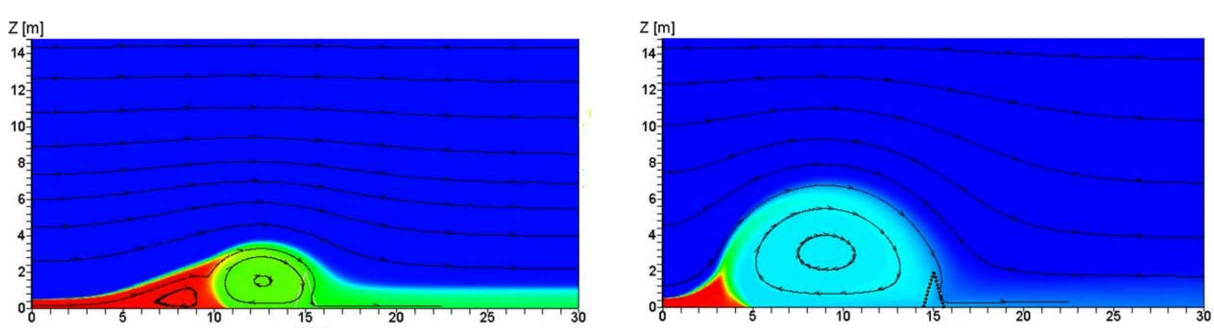
The droplet phase is described by a Lagrangian approach where single droplet injections model the particulate flow at the nozzle exit. The droplet velocity is calculated by solving the motion equation, taking into account the drag and gravity forces. No droplet-to-droplet interactions like collision or particle break-up are considered. Injection of the droplets at the floor or at a given altitude, respectively, may reproduce upward or downward spray curtain. The Rosin–Rammler droplet size distribution models the poly-dispersed nature of the spray, which is also described by a sufficiently large number of droplet trajectories initialized at the exit of the nozzles. The two-way coupling between the gas and droplet flow is taken into account by the implementation of momentum and energy source terms in the equations (Buchlin, 2003).

The numerical simulations are two-dimensional. In the near future, three-dimensional simulations are scheduled to be closer to the field tests configuration.

5. Results

5.1. *Efficiency quantification*

The concentrations are measured successively for a free and for a forced dispersion case. The water curtain efficiency, or the resulting concentration reduction, is



(a) R_M =2.0 (b) R_M =10

Fig. 5. Numerical concentration maps.

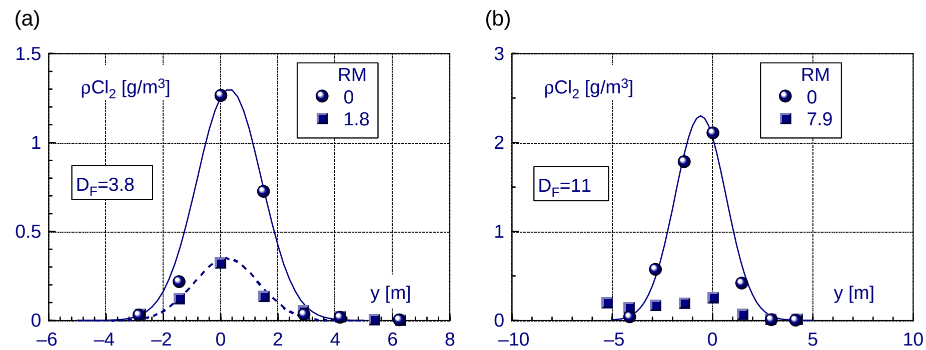


Fig. 6. Lateral ground concentrations downwind of the water-curtain.

expressed in terms of the dilution factor D_F defined as the ratio of the ground concentration without and with sprays:

$$D_F = \frac{C_{\text{free\_dispersion}}}{C_{\text{forced\_dispersion}}}.$$

This dilution factor is plotted versus the momentum ratio R_M, which is defined as ratio of the momentum of the water-curtain to a representative momentum of the gas cloud:

$$R_M = \frac{\dot{m}_{l,u} U_{d0}}{\rho V^2 H_{wc}}$$

where $\dot{m}_{l,u}$ is the liquid-flow rate per unit length, U_{d0} is the initial droplet velocity at the nozzle orifice, ρ is the cloud density, V the wind speed and H_{wc} the height of the water-curtain.

5.2. The D_F–R_M evolution

From the different approaches, visualization and result analysis indicate that the momentum ratio is indeed a good gauge to typify the potency of the water-curtain. Visualizations from field tests (Fig. 2) and from the Wind-Gallery experiments (Fig. 4) and concentration map from numerical simulations (Fig. 5) provide a clear image of the process.

At low momentum ratio, the gas cloud goes through the curtain without noticeable concentration modification. As R_M increases, the strength of the curtain with respect to the wind intensifies, and a windward recirculation zone upstream the water curtain forms.

At moderate R_M, typically 2, a large amount of pollutant goes through the water-curtain.

At high R_M values, typically 10, the water-curtain has a strong effect and starts to behave as an active obstacle for the gas cloud. Due to the air entrainment in the spray, the gas cloud at the ground level will meet an upwind air stream and the windward recirculation bubble increases in size.

The size of the recirculation bubble and the concentration reduction downwind of the water-curtain are related as indicated by the concentration maps shown in Fig. 5.

The R_M value at which a change in the cloud-curtain interaction is observed, has been sought out in the field tests and in the Wind-Gallery experiments. In the field tests, a radical change is observed at $R_M = 4$. This is confirmed by the Wind-Gallery tests, where the range $3 < R_{-M} < 5$ is regarded as the transition region between small and large R_M.

5.3. Concentration distribution

In the field tests the concentrations have been measured at ground level, 3.5 m downwind of the water-curtain.

Typical lateral concentration distributions are plotted in Fig. 6 for free and forced dispersion cases and two different R_M values. The effect of the R_M is obvious. At moderate R_M-value, the concentration distribution remains gaussian even

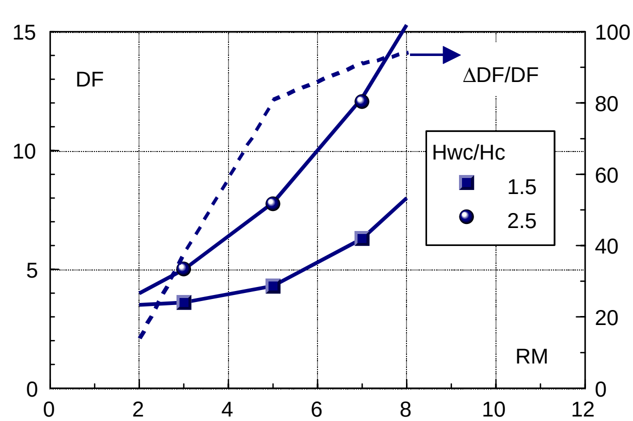


Fig. 7. Effect of the curtain-to-cloud height ratio on the forced dispersion factor.

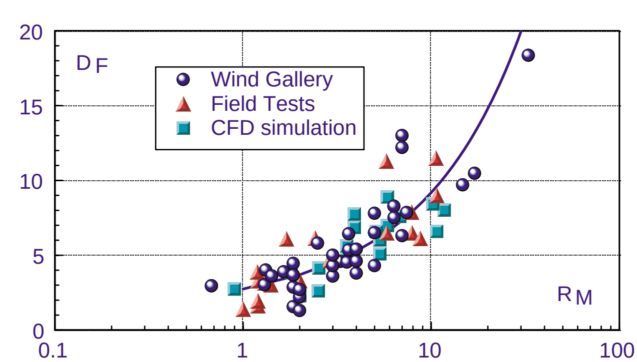


Fig. 8. Comparison of the results obtained with the three approaches.

in the forced dispersion situation. For high R_M-value, R_M, the lateral concentration distribution becomes flatter and the dispersion factor increases consequently.

5.4. Ratio of water-curtain to gas cloud heights

The effect of the curtain-to-cloud height ratio, H_{wc}/H_c, on the dispersion factor has also been investigated. The tests have been conducted in the Wind-Gallery. The height of the gas cloud considered is the cloud thickness at the curtain location during free dispersion experiment. The H_{wc}/H_c ratio has been modified by changing only the H_{wc}-value. Typical results are plotted in Fig. 7. It is worth noting that the effect of the height ratio on the dispersion factor becomes more significant as R_M increases. However, at high R_M the trend tends to saturate as shown by the dash curve ($\Delta D_F/D_F$) in plotted in Fig. 7. As a practical rule, a water-curtain more than twice the height of the gas cloud is recommended.

5.5. Comparison of the results obtained by the different approaches

The dilution factor obtained from the three approaches is plotted versus the momentum ratio R_M in Fig. 8. Despite the scatter of field test data resulting from variation of wind conditions (intensity and direction) and the different values of the curtain-to-cloud height ratios, the fair agreement observed between the three approaches denotes that the D_F–R_M is a pertinent representation of the forced dispersion by water-spray curtain.

Finally, all the approaches lead to the conclusion that at low wind speed, for which industrial spray curtains can readily function at a momentum ratio equal to or higher than 10, a dilution factor of 10 or more could be reached. At strong wind, the momentum ratio may fall down to 1 and then the cloud dilution will not easily exceed a factor 2.

6. Conclusion

Different approaches to study the dispersion of a heavy gas cloud by a water-spray curtain are presented. The methodology compares medium-scale field tests with laboratory experiments and CFD simulation. The final objective is to elaborate a robust and consistent database to put the finishing touches to an engineering design code of industrial water spray curtains developed at the VKI.

The good agreement observed between the different approaches emphasizes the important controlling effect of the curtain-to-wind momentum ratio R_M on the dilution factor D_F. As a general rule of thumb it can be stated that if the curtain-to-cloud height ratio is sufficiently large, a R_M-value of 10 should lead to D_F-value of 10.

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