ANALYSIS OF THE DISPERSION OF LARGE UNCONFINED CLOUDS FOLLOWING A MASSIVE SPILLAGE OF LIQUID HELIUM ON THE GROUND

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Abstract: Because of hydrogen's low volumetric energy content under its gaseous form, transport and storage of liquid hydrogen will inevitably play a major role in any future hydrogen economy. One of the obstacles to the expected development of the use of liquid hydrogen is the poor state of knowledge on dispersion and explosion hazard in the event of extensive spillage. In order to better understand spillage scenarios, INERIS has set up a large-scale experiment to study the gas cloud formation and dispersion mechanisms resulting from such a spillage and the corresponding mixing process and associated turbulence effects. Large scale dispersion tests have been performed with cryogenic helium presenting similar dispersion characteristics to liquid hydrogen (temperature, buoyancy). Flow rates up to 3 kg/s have been investigated with instrumentation to observe and measure buoyancy effects including internal turbulence. The results bring an original set of data of temperature and velocity fluctuations which can be used as a basis for the development of atmospheric model dispersion in the near field. The proposed paper will present the experimental set up as well as results and their interpretation.

Key words: *turbulence mechanism, fluctuation, buoyancy, atmospheric dispersion*

INTRODUCTION

Projections regarding the future development of the distribution of energy sources show a very probable increase in hydrogen consumption. This increase will require the creation of large storage facilities, and the packaging method that appears to be the most suitable is storage in liquid form (liquid hydrogen or LH2) at 20 K and at atmospheric pressure (Daun, 1993; Gretz *et al.*, 1990).

However, the main technological obstacle to the wider use of this kind of storage facility is undoubtedly the poor state of knowledge about the risks of explosion in case of a containment failure. A few attempts have been made to develop simulation tools but their results have met with much criticism owing to the lack of experimental data to validate the initial hypothesis (Lodhi and Mires, 1989) especially for cryogenic spills. In particular, the analysis of existing data shows that the violence of an explosion cannot reasonably be estimated unless the mechanisms controlling the formation of the cloud have been clarified and quantified (Proust, 1999).

The main aim of the present work is to provide information on these mechanisms and, at a first stage, to quantify the mixing processes and the associated turbulence effects during cryogenic spills.

EQUIPMENT

From a rather basic preliminary analysis (Proust, 1999), it has been found that buoyancy may play a significant role in the dispersion behaviour and since buoyancy forces are strongly size dependent, any representative test should be performed at the real scale (typically spill rate of about 1 kg/s). In order to avoid problems regarding the explosivity of hydrogen-air mixtures, liquid helium has been used instead which has similar physical characteristics to hydrogen (Proust, 1999).

The spillage system consisted of two Liquid helium trucks connected to vacuum thermally insulated lines. Tests were done with maximum flow rates of 1.5 kg/s and 2.1 kg/s respectively.

Instrumentation

Metrological equipment has been designed in order to obtain all possible useful information on the dimensions of the cloud, on internal temperature gradients and on the fluctuations of those scalars. Detailed description of metrological equipment was given in previous papers (Proust, 1999; Proust *et al.*, 2007). As a consequence, metrological equipment is briefly described in this paper.

The basic instrumentation consisted mainly of K thermocouples with a sufficiently thin stainless steel protective sleeve (the diameter of the sleeve of 250 m) to allow fairly quick measurement (10 Hz).

In an attempt to obtain some information on the aerodynamics of the cloud, the concept of " bi-directional probes " of Mc Caffrey has been adapted (Mc Caffrey *et al.*, 1976). It has been demonstrated (Proust, 1999) that this device allows us to determine the cloud velocity and its fluctuations as long as the scale of turbulence is not too small (not less than 10 cm).

The whole instrumentation has been installed on a net of steel ropes (Figure) held vertical in the wind direction by two cranes. The mesh has been defined using a contour plotting software package (SURFER). The mesh is " tighter " near the spillage point (space steps of 2.5 m, 5 m, 10 m were used in horizontal and vertical direction) than at the other end of the measuring field (space steps of 15 m, 30 m). More than 100 sensors were installed on a vertical rectangular frame (60 m x 130 m).
A few temperature sensors have been also installed near the spillage point to estimate the size of the liquid pool and to deduce the thermal power absorbed during vaporization. The tests were also filmed.

The information collected concerns the evaporation process, the structure of clouds and the inner turbulence.

RESULTS

Shape and structure of clouds



Figure 1. View of a part of the experimental arrangement showing the spill point and vertical steel ropes

A test database has been set up to investigate the incidence of the wind speed and flow rate onto the shape of the cloud (table1). This shape (Figure 10) is characterized by three parameters: L being the length of the cloud on the ground, H1 being the height of the base of the cloud, and H2 being the height at the top of the cloud. The tests showed that the cloud shape depends essentially on the flow rate and little on the wind speed (see Table 1).



Figure 10: Example of a liquid helium cloud (test 7)

Table 1. Main parameters concerning the dispersion of liquid helium and shape of the visible cloud (parameters defined in the text)

Issue n°	duration (s)	Mass flow rate (kg/s)	Wind speed (m/s) at 3 m height	Humidity (%)	Temp (°C)	H1 (m)	H2 (m)	L (m)
0	60	1.5	6	/	16	3	5	20
1	50	1.4	4,0±1,0	86	17	5	17	50
2	52	1.4	5,2±1,0	90	17	5	17	50
3	52	2.1	3,0±0,5	84	12	12	32	80
4	43	2.1	4,0±0,5	84	12	7	35	75
5	34	2.1	5,5±0,5	88	12	7	30	70
6	43	2.1	4,5±0,5	88	11	7	30	70
7	63	1.2	2,0±0,5	85	12			
8	65	1.2	2,0±0,5	85	12			
9	71	2.2	2,0±0,5	85	12			

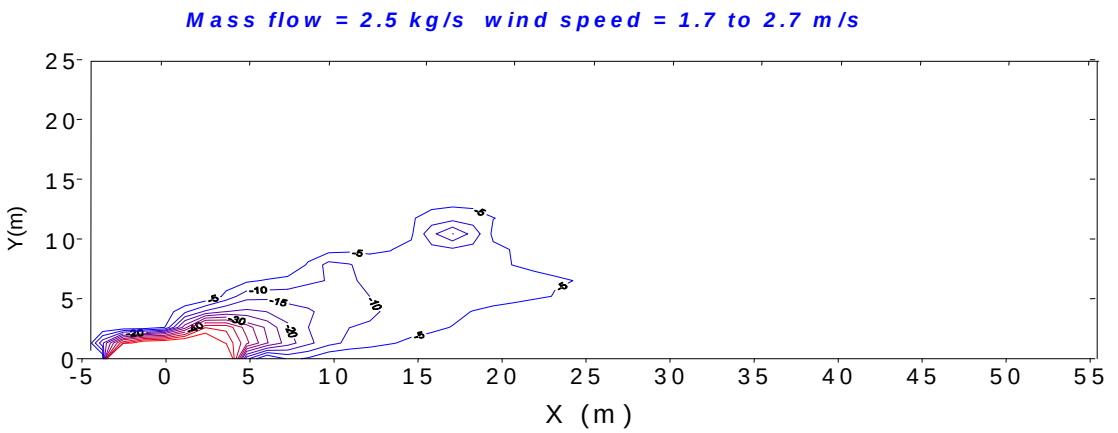


Figure 3 : Isotherms far from the spillage point. The plume is driven by an upward motion which gives the cloud an angle of approximately 30° with respect to the horizontal

In these tests, we verified that the visible shape of the cloud coincided fairly well with the isoconcentration curve (isotherm) corresponding to the atmospheric dew point. This information could be used to reinterpret available liquid hydrogen spillage test on which the only available information is visual (Mc CAFFREY *et al.*, 1976; Witcofski *et al.*, 1984).
The SURFER software package was used to determine the shape and location of isothermal lines by using the interpolation methods adopted during the definition of the mesh of the " net " of thermocouples (Figure).

Analysis of these results shows that the plume is driven by an upward motion which gives the cloud an angle of approximately 30° with respect to the horizontal. The upward velocity would be between 1 and 2 m/s and appears to be relatively consistent with other published data (Witcofski *et al.*, 1984). No clear dependence on the wind speed could be established, perhaps owing to the limited range of variation. On the other hand, the maximum extension of the cloud and its thickness seem to depend significantly on the spillage flow rate. If, for example, we take the -5°C isotherm as the reference (2 to 4% vol. of gas in air), the maximum extension of this surface area would be located at 15 m for a flow rate of 1.3 kg/s and at 25 m for a flow rate of 2.5 kg/s. The maximum radii of the cloud would be 5 m and 10 m respectively.

Finally, the temperature gradients are approximately 4°C/m (i.e. 3% per m according to the calibration curve of figure1) along the axis of the cloud and approximately 7°C/m (6% per m) perpendicularly to that axis for a flow rate of 1.3 kg/s. These values are considerably greater than those obtained with most of the current dispersion calculation tools.

Observed Fluctuations and Mixing mechanisms
The internal turbulence of the cloud is responsible from the mixing of the gas with the surrounding atmosphere. A specific analysis of temperature and velocity fluctuations has been conducted to clarify the effect of atmospheric turbulence and buoyancy forces.

In the case of atmospheric turbulence, it has been noted that velocity and temperature fluctuations represent 15% and 3% of the mean values and that the size of the large structures of this turbulence is approximately equal to half the distance between the measuring point and the ground.

When a helium cloud is present (Figure), the intensity of velocity fluctuations is between 50% and 100%, i.e. five times greater than in the case of atmospheric turbulence.

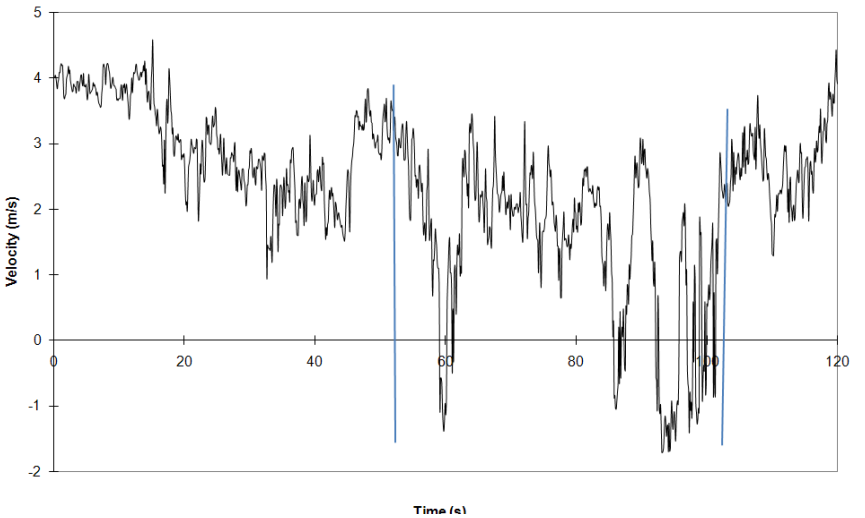


Figure 4: Velocity fluctuations in atmospheric turbulence (before point 40 and after 100) and with the passing of a helium cloud (range 40-100) (test 7)

The same applies to temperature. A sample temperature series is given in Figure . This series is very irregular and shows the local heterogeneous behaviour of the cloud.

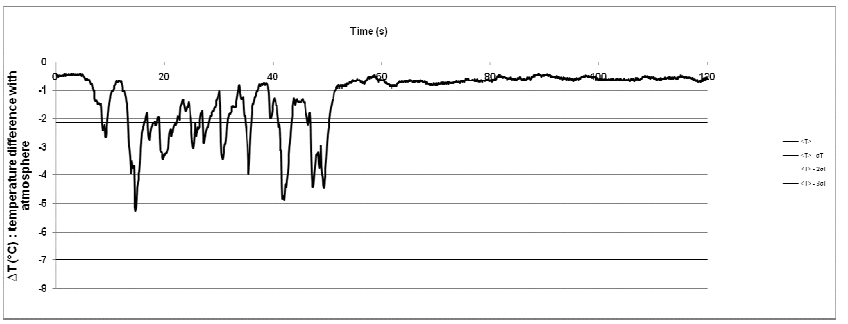


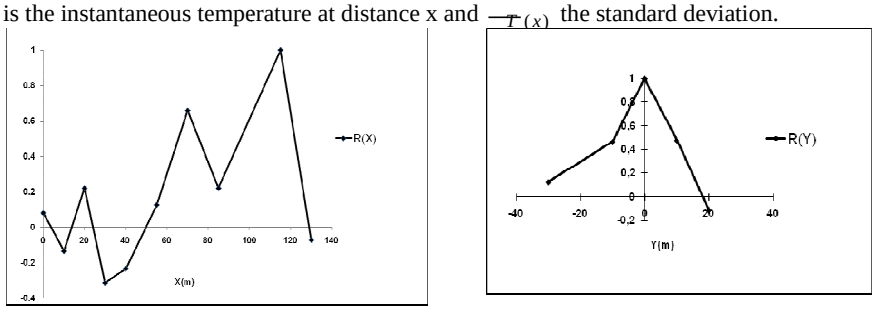
Figure 5: Sample temperature series, comprising values digitized values at a rate of 10 Hz from a temperature sensors located at (X= 2,5 m; Y = 0 m) from the spillage point (test 3). The mean concentration <T> and standard deviation σ_T are included on the graph.

Median time duration of this fluctuation is around 5 s. This result is of the same order than those mentioned by Witcofski and Chirivella (1984). The size of the large structures of turbulence at a height of 20 meters is approximately 2.5 m for a flow rate of 1.3 kg/s and 5 m for a flow rate of 2.5 kg/s, irrespective of the distance from the ground.

In order to investigate internal structure of turbulence, spatial correlation coefficient have been calculated . Examples of correlation between neighbor sensors are displayed on Figure . The horizontal spatial correlation function between two sensors separated by a distance x, is defined as

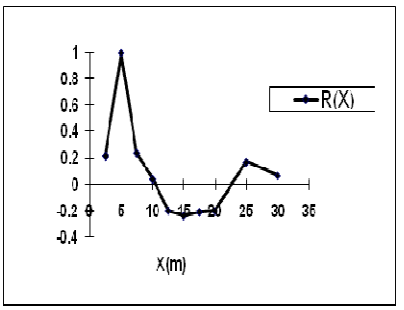
$$R(x) = \frac{\overline{(T(0) - \overline{T(0)})(T(x) - \overline{T(x)})}}{\sigma_{T(0)}\sigma_{T(x)}} \qquad (1)$$

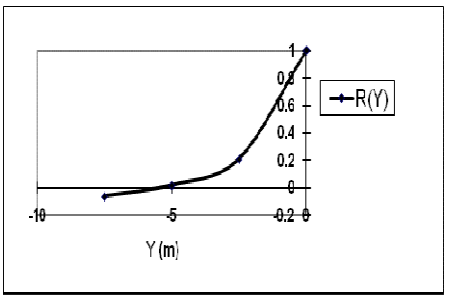
where $T_1(x)$ is the instantaneous temperature at distance x and $\overline{T(x)}$ the standard deviation.



(b)

Figure 6: Spatial correlation along horizontal (a) and vertical (b) axe around a receptor located at 120 m from the spillage point and 30 m from the ground (2,7 m/s mean wind velocity; test 3). X, and Y are relatively indicated from the release point and from this point located at 30 m in height respectively.





(b)

Figure 7: (a) spatial correlation along horizontal axe around a receptor located at 5 m from the spillage point and at 5 m from the ground (test 3). X is indicated relatively from the spillage point; (b): spatial correlation along vertical axe around a receptor located at 15 m from the spillage point and at 10 m from the ground (test 3). Y is indicated relatively from this point located at 10 m in height.

We could observe a pseudo periodic variation of the spatial correlation along horizontal axis. This variation could be explained by the presence of coherent structure in the field of turbulence as an eddy that appears close to the ground and is growing during its advection. Meanwhile such structures don't exist for spatial correlation along vertical axis, where observed variations (Figure (b) and Figure (b)) seem more classical. The value of the periodicity is around 20 m and independent of the altitude as we can see in Figure . This value is consistent with the dominant frequency on sample temperature series. A periodic variation is also observed in the evolution of the gas curl formed from contact of liquid helium with the plate. The presence of curl is similar to smoke dispersion during a fire where buoyancy forces are crucial parameter.

CONCLUSIONS

These results seem to indicate that buoyancy forces can play a very significant part in the process of cloud formation and not a marginal part as is often considered (mainly as a vertical advection effect). It is therefore estimated, on the basis of current data, that the intensity of turbulent transport (coefficient of turbulent diffusion) in the clouds studied is at least twice as great as that for atmospheric turbulence alone and that this effect increases with the quantity of liquid discharged.

Efforts are currently underway to carry out a complete spectral analysis of sample series in order to reproduce numerically with an appropriate model the physics of the dispersion in the near field of a light cryogenic gas.

Main trends may be already extracted from the present data, in view for instance to highlight in which spillage conditions severe explosions or toxic effects may occur. The starting point is to realize that buoyancy governs the formation of the cloud and its aerodynamics, including turbulence. The larger the flow rate, the larger the size of the cloud, the larger the turbulence intensity.

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