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PROCESSES OF THE FORMATION OF LARGE UNCONFINED CLOUDS FOLLOWING A MASSIVE SPILLAGE OF LIQUID HYDROGEN ON THE GROUND

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ABSTRACT:

Because of hydrogen low volumetric energy content under its gaseous form, transport and storage of liquid hydrogen will certainly play a major role in any future hydrogen economy. One of the obstacles to the expected development of the use of hydrogen is the poor state of knowledge on explosion risks in the event of an extensive spillage. INERIS set up a large-scale experiment to study the mechanisms of the formation of the gas cloud resulting from such a spillage and the associated mixing process and turbulence effects. Dispersion tests have been performed with cryogenic helium presenting similar dispersion characteristics than liquid hydrogen (buoyancy). Flowrates up to 3 kg/s have been investigated and the instrumentation allowed the observation and quantification of buoyancy effects including internal turbulence. Those results constitute an original set of data which can be used as a basis for the development of dispersion software and reinterpretation of other existing databases ([10, 11]).

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([1,6]).

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 ([7]) 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 ([8]).

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 [8], 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 [8].

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 ([8]) has been designed in order to obtain all possible useful information on the dimensions of the cloud, on internal concentration gradients and on the fluctuations of those scalars. Even for flow rates of a few kg/s, the analysis of existing data suggests that the cloud can be very large with lengths and heights of several tens of meters, requiring an extensive and relatively robust instrumentation. We verified experimentally, with small quantities of discharged liquid helium, that the helium-air mixture is rapid enough not to remain in contact with the ground and is thus adiabatic. In these conditions, the measurement of the temperature is a mean to obtain the concentration and density. The basic instrumentation consisted mainly of K thermocouples with a stainless steel protective sleeve sufficiently thin (the diameter of the sleeve of 250 μm) to allow fairly quick measurement. It has been checked experimentally at small scale (Figure 1) that the theoretical correlation between concentration and temperature is well supported by the experiments knowing air humidity plays a significant role.

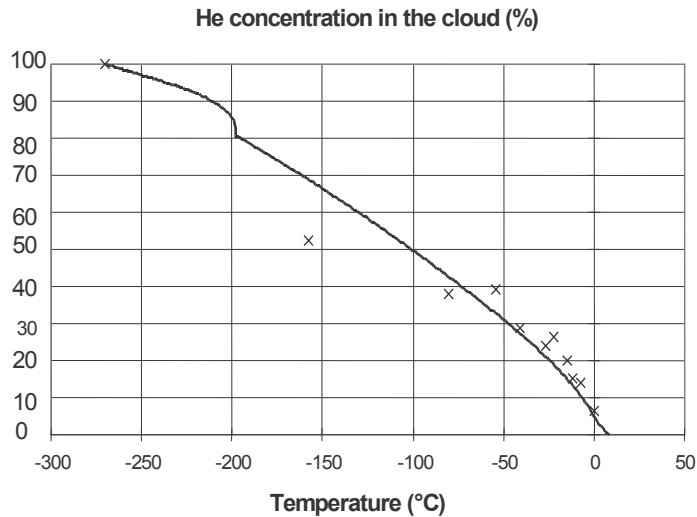


Figure 1. Concentration-temperature relation during the spillage of small quantities of liquid helium (concentration deduced from O₂ content).

In an attempt to obtain some information onto the aerodynamics of the cloud, the concept of “bi-directional probes” of Mc Caffrey has been adapted ([9]). This is a variation of the “Pitot tube” technique. By means of wind tunnel tests in particular([8]), it has been demonstrated that this device allows us the determination 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 2) 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 than at the other end of the measuring field. 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 2. 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 3) is characterized by three parameters: L being the length of the cloud on the ground, H_1 being the height of the base of the cloud, and H_2 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 3. 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			

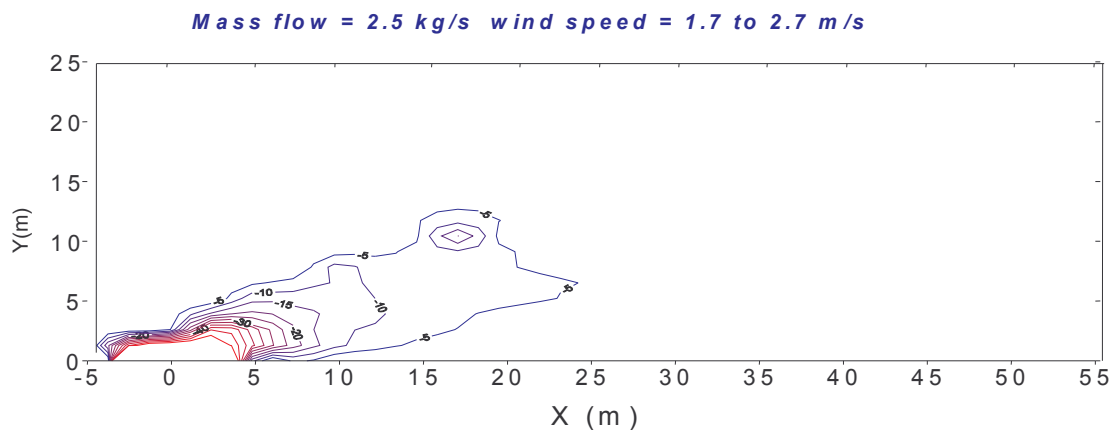


Figure 4. Isotherms far from the spillage point. The plume is driven by an upward motion which gives the cloud an angle of approximately 30° with respect to the horizontal

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 ([10, 11]).

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 4).

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 ([10]). 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 $4^{\circ}\text{C}/\text{m}$ (i.e. 3% per m according to the calibration curve of figure1) along the axis of the cloud and approximately $7^{\circ}\text{C}/\text{m}$ (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.

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 5), the intensity of velocity fluctuations is between 50% and 100%, i.e. five times greater than in the case of atmospheric turbulence. The same applies to temperature. 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.*

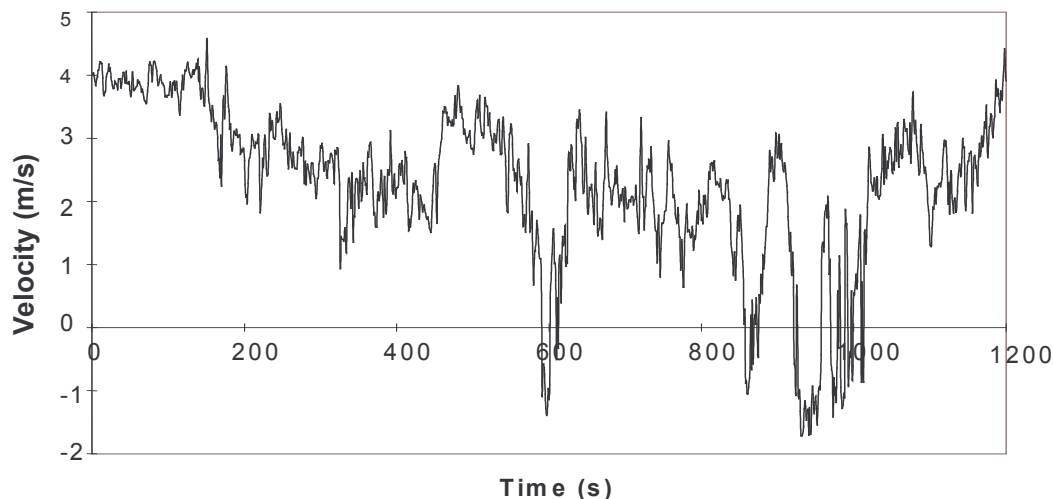


Figure 5; Velocity fluctuations in atmospheric turbulence (before point 400 and after 1000) and with the passing of a helium cloud (range 400-1000).

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.

At this stage, attempts to reproduce numerically the physics of the dispersion of such a “light” cryogenic gas as helium or hydrogen were not successful but the work is going on. However, main trends may be extracted from the present data, in view for instance to highlight in which spillage conditions severe explosions 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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