

THE USE OF FLUID CURTAINS FOR POST-RELEASE MITIGATION OF GAS DISPERSION

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The European Process Safety Centre is an industry-funded organisation which exists to provide an independent technical focus for process safety in Europe. The centre has four main objectives: information; research and development; legislation and regulations; education and training. In pursuit of the R&D objective EPSC has contracted the Department of Industrial Safety of the TNO Institute of Environmental Sciences, Energy Research and Process Innovation, based in the Netherlands, to investigate the use of fluid sprays for the mitigation of gas dispersion. The prime objectives of this investigation being:

- To produce a comprehensive overview of the current practices with respect to the use of water and steam curtains in Europe.
- To give an overview of the design guidelines for water and steam curtains.
- To contact competent authorities to find out how the regulations vary from state to state.

Keywords: fluid curtains, mitigation, gas dispersion,

INTRODUCTION

The post-release mitigation systems used in industry include fixed water spray installations, mobile water spray monitors and vapour or steam curtains. Their simplicity, flexibility and adaptability to very different operating conditions, together with their relatively low cost, have led to thorough investigations of their real capability to dilute, disperse and finally inhibit pollutant clouds.

Fixed installations allow rapid response to an emergency, especially when the water spray can be activated automatically by gas sensors. Also there are clear advantages in achieving mitigation without bringing the lives of emergency response crews and site personnel in danger. The advantage of a mobile monitor is the flexibility of when, where and how to apply. A mobile curtain also has the advantage that the fluid, usually water, can be employed more effectively since the position of the leak and the wind direction are known.

The European Process Safety Centre (EPSC) initially performed a survey among its member companies on their use of fluid curtains as a mitigation tool. The survey showed that several companies use water and steam curtains to mitigate the consequences of accidental releases of toxic and flammable materials.

As a follow-up to this survey, the following activities have been performed by TNO to meet the prime project objectives:

- ***Literature review***

In the first phase of the project a literature survey was completed[32], which resulted primarily in an overview of important design parameters and available models to predict the efficiency of fluid sprays in mitigating an accidental gas release.

- ***Site visits***

In the second phase of the project site visits were made to some selected EPSC member companies, to obtain detailed information on the fluid curtain installations. Some visits were also made to scientists involved in fluid curtain research.

- ***Telephonic interviews***

Telephone interviews were carried out with a number of other companies to collect information additional to the information collected during the site visits. The objective of the telephonic interviews being to acquire missing information on the use and design of fluid sprays in the process industry.

USE OF FLUID CURTAINS WITHIN EUROPE

The European Process Safety Centre performed a survey among its member companies on their use of fluid curtains as a mitigation tool. 25 responses from 22 companies have been received. The survey showed that most of the companies use water and steam curtains to mitigate the consequences of accidental releases of toxic and flammable materials:

- 3 companies use fixed water curtains, fixed steam curtains and mobile water monitors
- 11 companies use fixed water curtains and mobile water monitors
- 1 company uses fixed steam curtains and mobile water monitors
- 4 companies use fixed water curtains
- 3 companies have no fluid curtain applications

The responses to the question on what fluid curtain techniques are used, and for what duties (against releases of which chemicals), is summarised in table 1:

Table 1. Fluid curtain techniques and duties within the companies

FIXED INSTALLATIONS	**CHEMICALS**
Water	HCl, HF, NH_3, Cl_2, Acetic acid, Bromine, C_2-C_4, amines, foaming acids, phosgene, butyleneoxide, CS_2, BF_3
Steam	Olefins
Steam/Ammonia	Phosgene
Water Solution	Bromine
MOBILE MONITORS	**CHEMICALS**
Water	For (small) releases of HCl, Cl_2, SO_2, NH_3, chlorosulfonic acid, Use of mobile monitors is often part of emergency plans, carried out by emergency response teams

The companies gave the following responses on the qualitative effectiveness or efficiency of their fluid curtains:

- "significant effectiveness" for phosgene (steam/ammonia)
- "very effective" for NH_3, HF and small bromine releases
- "effective" for separating flammables from fired heaters
- behind the curtain the concentration was below MAC or LEL

- "results not impressive" on large leak of HF with fixed spray, small leaks attacked with firewater monitors "generally more successful"
- unknown (12 responses)

The only quantitative response gave an estimate of efficiency at 15-20% for water curtains on NH_3 storage.

FLUID CURTAIN RESEARCH

Fluid curtains are used to mitigate the consequences of dispersion of flammable and toxic releases in the environment. A fluid spray directed vertically, horizontally or at different angles (e.g. 45°) through a gas cloud will have a number of mitigation effects. These include:
(1) mechanical effects of acting as a barrier to the passage of gas;
(2) mechanical effects of dispersion and dilution by air entrainment;
(3) mechanical effects of imparting upward momentum to a gas;
(4) thermal effects by heating of gas;
(5) thermal effects by cooling in case of a hot or burning gas;
(6) physico-chemical effects of absorption of gas, with or without chemical reaction.

A lot of experimental work and modelling research on mitigation performance of fluid curtains has been performed. Several small scale laboratory tests and large-scale field tests have been conducted. Theoretical research and modelling programs resulted in the development of models to be used in fluid curtain design and for the prediction of the spray efficiency. The fluid curtain research, both the experimental and theoretical work, provided information on the influence of various curtain design parameters on the mitigation performance of fluid curtains.

The aim of two major large-scale experimental tests, the Goldfish tests[4] and the Hawk tests[24], was to assess the effectiveness of water curtains for hydrogen fluoride (HF) release mitigation. For these and for other experimental tests measured efficiencies of fluid curtains in reducing downwind concentrations are provided. These measured efficiencies are summarised in table 2. More detailed information is given in the description of the various experiments in the draft report of the project[32].

Table 2. Overview of measured efficiencies for some experiments

Experimental tests	Measured efficiency
Goldfish tests[4]	Water curtain spray systems achieved approximately a 36% to 49% reduction in downwind concentrations of HF at a water-flow/acid-flow ratio of 20:1.
Hawk tests[24]	HF removals of 25% to 90% were demonstrated at water-to-HF liquid volume ratios of 6:1 to 40:1.
Steam curtain tests[2]	It was proved that a mean dilution factor of 6 to 66 can be achieved at curtain working pressures of 2.5 bar to 10 bar overpressure.
Water and steam curtain tests[21]	Typical concentration reduction factors for steam jets 15 m downwind of the curtain were less than 4, compared with 4-16 for upward water sprays.
Water curtains to protect fire fighters[1]	The effectiveness of the water curtain has been confirmed, since concentrations behind this kind of barrier fall by a minimum factor of 3 at a distance of approximately 20 m, and a factor of 10 at least at 13 m.

It can be concluded from the above experimental work that significant efficiencies can be obtained by applying fluid curtains. Nevertheless, the achieved efficiencies strongly depend on the conditions of the experiments.

In Industry some methods are in use for predicting the effectiveness of fluid sprays on gas dispersion. Some simple models are available to predict air entrainment and dilution factors resulting from application of a fluid spray[18]. Semi-empirical models for dilution by entrainment of air are developed[21], which agree with experimental results for water and steam curtains. Theoretical and experimental results indicated that one of the key parameters controlling the effectiveness of forced dispersion is the ratio of the air velocity induced by the sprays to the wind speed.

Major research programs resulted in the development of two sophisticated spray models which can be used in the design of fluid curtains:

(1) The HGSPRAY model[13] was developed to study and predict the effectiveness of fluid curtains in mitigating heavy gas releases and to be able to aid in the design of mitigation systems.

(2) The objectives of a Co-operative European Research Program[16,27] were to gain more comprehensive understanding of sprays to predict more accurately the mitigation potential available and to optimise the curtain design for toxic gas dispersion. The engineering code developed in the frame of the project can be used to design spray curtains to mitigate accidental releases.

PARAMETERS DESCRIBING THE EFFECTIVENESS OF FLUID SPRAYS

In table 3 below an overview is given of the curtain, site and meteorological parameters, which were studied in the various experiments and modelling programs. Study of these parameters provided insight in the influence of various design parameters on the mitigation performance of fluid curtains, and gave an overview of the parameters which must be taken into account in designing fluid curtains.

For convenience, the parameters are classified in four categories:

(1) fluid curtain configuration;
(2) spray and nozzle parameters;
(3) release conditions;
(4) meteorological conditions.

A summary of the influence of the parameters, which are given in table 3, on the effectiveness of fluid curtains is given below. This information is extracted both from experimental and modelling research. Study of these parameters and their influence on fluid curtain effectiveness provided insight in which parameters must be taken into account in designing fluid curtains.

Most attention is given to the influence of the parameters on the

- barrier,
- dilution and
- absorption effects of fluid curtains.

The influences of the parameters on these three curtain effects can differ significantly. For example, a fine water droplet size will result in small barrier and dilution effects, but enhances absorption of the pollutant in water.

A difficulty is introduced by the fact that the influence of some parameters strongly depends on the experimental conditions. For example, increasing a parameter may result in a higher mitigation efficiency in one experiment, and in a decreasing efficiency in a second experiment.

Table 3. Studied parameters in fluid curtain research

(1) Fluid curtain configuration
• Fixed curtain or mobile monitor
• Water or steam curtains
• Curtain distance from release point
• Curtain elevation (spray height)
• Spray direction (direction of fluid flow)
• Multiple spray curtains
• Use of additives
(2) Spray and nozzle parameters
• Fluid liquid volume rate
• Curtain (nozzle) pressure
• Water spray droplet size
• Nozzle types
• Nozzle spacing
(3) Release conditions
• Type of released material
• Amount of material
• Density of released material
• Release pressure
• Release temperature
(4) Meteorological conditions
• Wind speed
• Wind direction
• Atmospheric stability
• Relative humidity

CURTAIN CONFIGURATION

Fixed curtain or mobile monitor

A fixed curtain and a fire monitor can have the same efficiency. However, to achieve this the fire monitor must then be operated close to the leak source and aimed directly at the release point.

Water or steam curtains

Some experimental tests[2] indicate that steam curtains have a mitigation efficiency which is comparable with water curtains. Other tests[21] showed the opposite, so no general conclusions can be drawn.

Curtain distance from release point

A fluid curtain must always be placed as close as possible to the pollutant source, to maximise contact between the water spray and the gas cloud and to minimise the length of the curtain. The fluid spray is most effective at points where the concentration is high, which is normally the case near to the source.

Curtain elevation (spray height)
The spray header must be placed at least above the height of the leak, otherwise severe bypassing of the water spray by the gas cloud is possible. However, if the cloud is deflected over the top of the spray curtain, this will in itself lead to an increase in the dispersion process.

Spray direction (direction of fluid flow)
A vertical spray curtain can be directed upwards or downwards. The upward system is more efficient in terms of dilution of the pollutant cloud, but a downward curtain does have a greater decelerating (barrier) effect.

Downwards sprays can be ineffective in strong winds, when the gas cloud can pass under the spray at ground level. For high wind speeds, vertical upward spray curtains based on coarse droplet distribution are recommended. Upward sprays induce significant air entrainment at all wind velocities, even though the spray may be deflected. Some experiments[5] showed that at high wind speeds horizontal sprays (directed towards the cloud) were more effective than down- and upflow.

Multiple spray curtains
Two curtains may optimise mitigation: a fine absorbing curtain between the source and a diluting coarse curtain. Application of two curtains with the same fluid rate results in a higher dilution effect than working with a single curtain. The use of two or at most three curtains in series can improve containment. The best results will then be obtained with equal water flows for each curtain. When two spray curtains are used the one with the larger water flow dominates the system.

Use of additives
For gases presenting low water solubilities such as chlorine (Cl_2), phosgene ($COCl_2$), hydrogen sulphide (H_2S) and nitrogen oxides (NO_x), the use of chemical additives in the water can strongly enhance the absorption effect.

SPRAY AND NOZZLE PARAMETERS

Fluid liquid volume rate
The fluid liquid volume rate was found to be a major variable affecting removal efficiency. Higher flow rates result in higher barrier and dilution effects and in higher removals of the pollutant.

High discharge capacity nozzles fed under high pressure create a violent action which results in a forced dilution. The limiting factors for dilution action are the liquid flow rates which can be realistically established in an industrial site. Particular attention must be paid to the availability of the water supply for the required duration and the retention and treatment of the waste water.

Curtain (nozzle) pressure
Research is clearly showing that greater curtain efficiency is achieved as the curtain pressure is raised (for both water and steam curtains).

High nozzle pressures result in a high water velocity, which induces a high air velocity. Although the effectiveness of air entrainment by water sprays is poor for high initial water velocities, the corresponding total entrained air flow rates are large. These considerations support the recommendation for the use of spray curtains with high initial water velocities.

Water spray droplet size

For drop sizes two competing mechanisms are determined by the experimental and theoretical work:

1. Smaller drop sizes result in a higher surface area, which increases absorption. However, if the droplet sizes are too small, the drops won't settle by gravity but will instead be transported downwind. In general an absorbing system has to be based on fine sprays with droplet sizes ranging from 100 to 300 μm to improve interfacial area and contact time of the liquid phase.
2. Larger drops result in higher momentum transfer and higher air entrainment rates, and thus in higher barrier and dilution effects. Larger drops are less influenced by atmospheric influences like wind speeds.

The most effective explosion-mitigating water-spray systems are those generating either very small droplets (less than 10 μm) or large droplets (larger than 200 μm).

The increase of liquid pressure improves the shielding performance against radiation from fires through the decrease in droplet size. The liquid break-up into tiny droplets induces an increase of the total surface opposed to the radiation and improves the back-scattering contribution. Moreover: the smaller the droplet, the smaller is its terminal velocity due to the momentum exchange, the longer is its residence time inside the curtain, the higher is the droplet concentration and the better is the radiative attenuation.

Nozzle types

A great variety of choice is possible, but the most important are the hollow cone, solid or full cone and fan tail sprays. The type of nozzle, and the spray pattern and droplet size distribution they produce, have a considerable influence on the operation of the water curtain. Only some conclusions can be drawn from research.

The flat fan sprays with a small flow number are promising for controlled rapid release purposes. These nozzles produce rather small drops with high initial velocities. The 40 jet nozzle system looks promising for containment purposes. These nozzles produce rather coarse drops with low initial velocities.

Nozzle spacing

A critical parameter for spray efficiency is the distance between the nozzles on a curtain (nozzle spacing). Generally, one can say that decreasing nozzle spacing is more efficient for the whole curtain system, but reduces the efficiency of each spray nozzle. Nozzle spacing is closely related to the type and size of nozzles selected and to their cone angle or fan size.

Experience shows that nozzle spacing should be such that adjacent sprays virtually impinge on each other in order to prevent passage of the cloud between sprays, especially at the base. The spray overlap induces higher drop and gas velocities reducing interfacial area per nozzle, but also reduces the risks of gas bypass between the nozzles. However, major overlap will tend to be inefficient.

RELEASE CONDITIONS

Type of released material

The released material can be flammable or toxic. In case of a toxic release the type of material and its solubility are important in that they determine the absorption effects. For highly water soluble gases such as hydrogen chloride (HCl), hydrogen fluoride (HF) and ammonia (NH_3) the absorption effects can be significant.

Amount of material
The fluid curtain is more effective for lower release rates of the pollutant. Lower release rates result in higher removals of the material.

Density of released material
Dense materials are less influenced by atmospheric influences like the wind speed than lighter materials. The higher the wind speed and the lighter the gas, the less effective the screen. However, it must be remembered that these are conditions which promote good natural dispersion.

Release pressure
With an increasing acid pressure an increasing efficiency was measured in the Hawk tests[24]. However, these measurements could not be explained.

METEOROLOGICAL CONDITIONS

Wind speed
Doubling of the wind speed from 3 to 6 m/s had a negligible impact on curtain efficiency according to the Hawk tests. Other experiments indicated that increasing the wind speed resulted in a decreasing effectiveness of the fluid curtain.

Experiments showed that the influence of wind speed decreases with increasing operating pressure of the nozzles and with increasing drop sizes. Theoretical results indicated that a denser curtain (low nozzle spacing, high fed pressure) performs better in strong winds, as its momentum is higher.

Wind direction
To ensure water-spray contact with the cloud wind direction must be taken into account. For releases directed against the wind under low wind speeds, a complete enclosure appeared necessary. A partial barrier may lead to escape of gas around the sides of the barrier. A water spray, which totally surrounds an installation, can also be operated and controlled such that only the downwind sections are activated.

Atmospheric stability
A fluid curtain is more effective as a barrier in a stable atmosphere (e.g. Pasquill stability class E or F) than in an unstable or neutral atmosphere (e.g. class A to D). As noted above natural dispersion is more effective under meteorological conditions with stability classes A to D.

SITE VISITS AND INTERVIEWS
In the second phase of the project site visits were made to some selected EPSC member companies. The survey of all EPSC member companies provided a list of company experts, which was used to follow up with more detailed questions during the site visits to these experts.

The objectives of these visits was to obtain detailed information on the current practices with respect to the use of water and steam curtains within the companies, and to collect information on the actual designs for fluid curtains.

Telephone interviews were also carried out with other companies to collect additional information to that collected during the site visits. The objective of the telephonic interviews being to acquire missing information on the use and design of fluid sprays in the process industry. Some visits were also be made to scientists involved in fluid curtain research.

FINDINGS FROM VISITS

It was found from the site visits that the reasoning behind a company's decision to install fluid curtains could be broken down into four areas:

- The isolation of ignition sources;
- The isolation of off-site population;
- The reduction of on-site toxic concentrations; and
- The reduction of off-site toxic concentrations.

Most companies were found to have equipment for providing mobile water curtains. However it became clear from the interviews that there was no industry consensus on:

- When to install fixed fluid curtains;
- How to design the curtains;
- The expected efficiency of a curtain design.

The interviews also discovered a difference in the approach taken by companies on the use of fluid curtains between those for flammable duties and those for toxic.

Flammable materials

For use with flammable material the visits showed that both steam and water curtains have been employed, and that older systems are still in use. However, although new systems were being installed by certain companies, others would not install fluid curtains on flammable duties for facilities being designed today.

The main concern on the use of fluid curtains for flammable duty was found to be the need for very rapid activation of the systems for them to be effective in providing a barrier between the flammable cloud and ignition source. In most cases the activation time required is very small and this leads to practical difficulties in the design and operation of the curtains and their associated activation systems.

Toxic materials

For toxic duty the visits showed that fluid curtains were used for only a very small number of applications. Reasons stated for not using or not having confidence in fluid curtains included:

- The lack of good guidance on their design and operation;
- The absence of design codes;
- No methods to estimate effectiveness;
- The testing of systems;
- The difficulties involved with the ongoing maintenance of systems throughout the systems lifetime.

CONTACT WITH COMPETENT AUTHORITIES

The original EPSC survey of its member companies and their fluid curtain installations established the basis for this project. The EPSC Mitigation of Gas Dispersion Contact Group received a very good response to this survey however, it did not make any reference to the requirements made upon these companies by the relevant country's Competent Authority. It was apparent that there was no pan-European regulation or legislation on the use of fluid curtains for the mitigation of gas dispersion. However, members of the Contact Group felt that it would be beneficial to discover if individual Competent Authorities have such regulations or if they make any recommendations on the use of fluid curtains for this duty.

THE QUESTIONNAIRES

It was decided that the necessary information would be best obtained through the use of questionnaires to the respective Competent Authorities. A two stage questionnaire was used:

- The first establishing if any requirements existed on the use of fluid curtains as a gas dispersion mitigation technique;
- While the second questionnaire looked to define the details of any such legislation.

The questionnaires were sent to sixteen Competent Authorities ranging from Greece to Iceland and Portugal and Finland.

The first questionnaire was designed just to briefly indicate whether there was any requirement by the Competent Authority for the use of fluid curtains.

THE RESPONSES

At the writing of this paper only responses to the first questionnaire had been received. The responses showed considerable differences between states in the types and form of national regulation, requirements, codes of practice and recommendations made. In some states there are strong pressures to consider fluid curtains, with some states including the request for the installation of fluid curtains in the “conditions” attached to a site. In other states little emphasis is placed on the use of fluid curtains. This is true for states that primarily base their decisions on the use of QRA and/or use models which do not take account of mitigation measures. It was also found that for certain states mitigation techniques in general, not just fluid curtains, did not receive “credits” during an assessments by authorities as opposed to preventative measures which did.

Overall from the responses received it become apparent that in the majority of states there are general requirements for operators to:

- “…….take all necessary measures…………….”; and
- “…….equip the facility with the necessary safety equipment….”;

Which can be interpreted as requiring operators to consider the installation of fluid curtains.

The findings from the second detailed questionnaires will be presented at the symposium.

CONCLUSIONS

Fluid curtains are widely used in industry to mitigate the consequences of accidental releases of toxic and flammable materials. Both fixed installations and mobile monitors are used, with many different techniques and designs, and against the releases of various flammable and toxic substances.

Qualitative and quantitative estimates of mitigation efficiencies show that under certain circumstances fluid curtains have the potential to provide effective mitigation of gas releases. In particular recent work in both the USA and Europe has shown that fluid curtains can produce significant mitigation effects when well designed systems are applied for soluble gases.

From the project findings it has become clear that there is however no consensus on their value either within industry or within the Competent Authorities. Important gaps in our knowledge need to be rectified if the use of fluid curtains is to be considered more widely. To increase confidence, improvements are needed in:

- Guidance;
- Design codes;
- Models of effectiveness/efficiency;
- Testing and the verification of effectiveness.

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