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Stack Releases During Low Winds, Evaluation of Hazards and Mitigation Using CFD

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Chemical and petrochemical facilities will have substances that may need to be released to atmosphere, either all the time or on special occasions like system maintenance situations or as a part of safety procedures during unwanted process safety incidents. As the substances are often toxic and denser than air, the typical solution has been to vent the substances from stacks at a significant elevation. While this solution may work well when there is significant wind, the gas plume may fall to the ground during low wind scenarios (< 1-2 m/s) exposing workers or neighbours of the facility to problematic gas concentrations. To ensure safe design of stack venting systems it is common to use integral models for dispersion predicting downwind distribution of gas. While standard integral consequence models may predict gas concentrations for wind dominated scenarios well, generally they cannot predict plume behaviour and hazards for the more critical low wind scenarios. For these scenarios gas plume density, slumping to the ground, effects of buildings, process plant geometry and topology are important. In this work CFD modelling has been utilized to better understand stack dispersion during low winds to be able to predict the hazards and identify the safe operational window. Among several interesting findings of the study was that worst-case concentrations at ground level may significantly increase with reduced stack flow rate, as the vertical upwards velocity and mixing with air are reduced. Several mitigation possibilities to reduce ground level gas concentrations during low wind scenarios exist. This study concluded that a frequently used approach of extending the stack had a very limited beneficial effect, while strong vertical fans next to the stack during low wind conditions could have a very beneficial effect reducing ground level concentrations.

1. Introduction

Petrochemical facilities will usually have substances they must vent to the atmosphere, either on temporary basis (e.g. safety blow down, maintenance shut downs) or permanently (e.g. turbine exhaust). If the substance is flammable and present in large quantities, it is usually burnt in a flare, to avoid the potential accumulation of flammable gas inside the plant. Inert or toxic substances, as well as smaller quantities of combustible material, may be sent to a vent stack. A main goal when designing a vent stack is that people, i.e. workers, visitors or neighbours of the plant, shall not be exposed to concentrations of concern. Substances being vented may also interfere with plant operations, e.g. lead to false triggering of gas detectors and initiate unwanted and costly safety actions.

To define concentrations of concern for various chemicals one source of information will be the legal limits set by local occupational safety authorities, for instance OSHA, EPA and NIOSH. The American Conference of Governmental Industrial Hygienists (ACGIH) is a membership organization developing a set of recommended exposure values which are also widely applied. Typically acceptable worker exposure levels are defined for 8h continuous exposure, for most substances a higher exposure is allowed for short durations (e.g. 150-200% for up to 10-15 minutes), while for other substances absolute ceiling values are defined, that can never be exceeded. Internal company standards of multinational corporations will normally be at least as strict as the legal limits in their main countries of operation. Often action limits are defined which may be a factor of two or more lower than the legal exposure limits, which force them to consider ways to reduce the potential problems.

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The substance released is often a mixture of various gases, or if it is one particular gas, there are traces of pollutants in the mixture. There may thus be several different limits to consider. One pollutant often present in natural gas as well as captured CO_2 is H_2S. In Table 1 a number of recommended maximum exposure limits are provided for H_2S. For a stack dispersion scenario one can assume that the gas composition remains unchanged while being diluted with air, thus if the initial H_2S concentration is 1000 ppm, it has been reduced to 1 ppm when the concentration of released gas is reduced to 0.1%.

Table 1: Example of exposure limits for H_2S from EPA, ACGIH, OSHA and NIOSH (internet sources)

Threshold (ppm)	10min	30min	1h	4h	8h	Comments
AEGL-1	0.75	0.60	0.51	0.36	0.33	EPA:Comfort limit
AEGL-2	41	32	27	20	17	EPA: Irreversible health effects
AEGL-3	76	59	50	37	31	EPA: Life threatening
PEL	50				10-20	OSHA: Permitted exposure limit
REL	10					NIOSH: Recommended exposure limit
ACGIH					1	http://www.acgih.org

Gases with positive buoyancy compared to that of air (e.g. hydrogen and natural gas) will in most cases dilute and disappear upwards after being vented. There are, however, situations where vent designs (e.g. high pressure T-vent), presence of aerosols in flow, premixing with colder than ambient air, large temperature differences (e.g. vapour from LNG or LH_2 on warm days) and local wind conditions may lead to exposure at lower lying locations. More of a concern is stack venting of dense gases, as these will with time fall to the ground. The goal of the stack design process will be to ensure that the concentrations of substances of concern are diluted to well below exposure limits at the time the plume hits the ground.

Some possible ways to achieve maximum dilution for a dense gas vented from a vertical stack can be:

- A tall stack will increase the time it takes the plume to fall to the ground, and the dilution.
- A narrow exit orifice will increase vertical flow velocity, and thus increase mixing by momentum, maximum height/length of trajectory and thus dilution of plume.
- A more wind-exposed location of stack can increase length of plume trajectory and dilution.
- Heating of gas prior to exit orifice will reduce its density and extend trajectory and dilution

The design of a stack is often an optimization process. Cost and design concerns will limit the height of a stack, while worker environment issues like noise and vibrations, and costs increasing the design strength, will limit the design vent flow velocity. Another issue to consider is that the flow rate may vary depending on process parameters. Since a lower flow rate will give significantly reduced plume velocity out of the stack, it will get less diluted by momentum and fall to the ground faster and more concentrated. Thus, a worst-case design using the highest flow rate may underestimate the potential hazards.

Wind speed and sometimes direction are essential parameters for stack performance. With a significant wind speed the plume trajectory will be long, the concentration well diluted, and the touch-down to ground far away from the plant. In cases where potential targets are elevated (e.g. offices or neighbours of plant on a downwind hill) a plume from an elevated stack may make a “perfect hit” of the target for certain wind conditions, leading to higher exposure levels than would be found at a similar distance at ground level due to a shorter plume trajectory. If the stack venting is continuous over days, or the need for stack venting is of stochastic nature (e.g. caused by activation of safety system), one must expect that venting may take place during low or no wind conditions for which the plume may hit the ground much less diluted in the vicinity of the stack inside the plant. No or low wind conditions are thus in most cases the major concern.

2. Models and methods used to evaluate vent stack performance

Numerous models have been developed to predict atmospheric dispersion and air quality. The majority use Gaussian plume assumptions to spread the gas laterally and vertically downwind, including those most commonly used to evaluate stack performance. Some major drawbacks with these models are that most will ignore the presence of geometry, like process plant structures, buildings and surrounding terrain, and assume a completely flat and unobstructed ground. And even if a flat ground is taken into account, the impingement and spread when a dense plume falls to the ground are not modeled by standard approaches. Another major weakness of Gaussian-based models is that these will only transport the gas downwind. For dense gas dispersion during low winds the plumes often migrate upwind due to gravity, and phenomena like recirculation behind buildings, preferential dispersion along depressions in the terrain and plume deflections due to large buildings or steep hills, which are all ignored by Gaussian modeling, may dominate the dispersion process.

Computational Fluid Dynamics (CFD) models can predict the phenomena more in detail and can take into account both geometry and the mentioned dense gas effects. Due to the weaknesses of Gaussian-based models mentioned above, CFD is used more frequently when accurate results are required. CFD is often required e.g. for exhaust plume studies on offshore oil and gas installations, see e.g. NORSOK Standard S-002, (2004) and for many types of LNG-dispersion studies according to the standard NFPA-59A (2009), where an evaluation process has been defined to qualify dispersion models. The FLACS CFD-tool used for the simulations in this paper, was as the first CFD-tool accepted for such studies in 2011 after a validation study, see Hansen et al. (2010). The validation/evaluation of CFD-models and their guidelines is considered very important as benchmarking studies in the past have revealed a significant variability in predictions among models and modelers, see e.g. Venetsanos et al. (2009).

As a consequence of the mentioned weaknesses with Gaussian-based dispersion models, one frequently used dispersion model Phast of DNV, will only provide dispersion predictions for wind speeds higher than 1 m/s, and can thus not be used to study worst-case low wind scenarios for stack releases. For wind-dominated scenarios with no obstructions influencing the plume, however, FLACS and Phast will give quite comparable predictions.

In order to perform a proper evaluation of a vent stack, including potential worst-case exposure to workers or locations in the vicinity of the stack, it is appropriate to apply a properly validated CFD-model. If there are obstructions of significant height compared to the stack, i.e. buildings or terrain, it will be worthwhile to simulate scenarios with wind from several different directions to evaluate maximum gas concentrations at ground level and defined targets. The stack flow rate and the flow/ambient temperatures should all be varied within their expected ranges as these parameters will influence the concentrations at targets. To predict the worst-case concentration for targets at elevated locations, a sensitivity study of wind velocity is required.

Based on the conclusions from the study, it should be evaluated to what degree the predicted concentrations are in conflict with the legal limits or company internal standards, and based on that evaluate if actions should be taken. Potential actions may include:

- Alarms and local evacuation, or temporarily shut-down of process, if concentrations above legal limits are detected, or when wind/release conditions indicate possibility for this.
- Design measures like increasing height of stack or higher flow velocity out of stack.
- Heating of gases to reduce density, or dilution with less dense gases (e.g. hot air).
- Fan systems next to vent that give additional vertical momentum and dilution when needed.

Many of these mitigation measures will have a good effect for some scenarios but may make others worse, it is thus important with a proper evaluation with variation of scenario parameters to conclude on the effect of a measure.

3. Stack dispersion study at a petrochemical facility

The study presented in this section has been inspired by an actual stack modelling study performed, but due to confidentiality issues the description of the facility is vague and partly wrong, and technical details and gas compositions are changed so observations presented are not representative for the actual study.

The facility is located with the sea shore to the South. To the NE there is a hill, while the areas to the NW and along the shore are flat. At the facility there is a need at irregular intervals to send to stack a gas mixture which is roughly 50% denser than air, at a rate between 15 and 30 kg/s. The stack is at 50m elevation, and the inner diameter is chosen to give an exit velocity of 30 m/s at the dimensioning flow rate (30 kg/s). The gas mixture contains a range of substances, and based on evaluation against legal exposure limits for the different substances the major concern is a 1000 ppm fraction of H_2S. One of the questions to be answered in the study is to what extent problematic of H_2S can be expected to appear at the plant or at an office building located on the hill NE of the plant, at an elevation slightly below the stack. Relevant H_2S exposure limits can be found in Table 1, the ACGIH limit of 1 ppm is by the company chosen as exposure level of concern, the legal limit is however one order of magnitude higher at 10 ppm. Workers will recognize the H_2S odour at less than 0.01 ppm, and may thus notice (and feel discomfort) when exposed to gases from stack well below thresholds, while eye irritation will be felt from 10-20 ppm.

A simulation study is performed evaluating stack releases for a number of scenarios with varying wind speed and direction. Maximum flow rate and ambient summer temperature conditions are assumed as worst-case, but sensitivity studies were performed and these identified e.g. that maximum flow rate may not always represent worst-case, e.g. at low wind speeds a lower release rate could give a significantly higher maximum concentrations at ground level (+50%) due to reduced vertical flow speed out of stack. To evaluate the potential exposure at the office buildings on the hill a sensitivity study was performed with varying wind speed from SW. In Figure 1 the 0.1% concentration plume is shown (corresponding to 1 ppm H_2S) shortly after stack release starts (left) and when properly developed (right) for wind speeds of 1 m/s (top), 2 m/s (2nd row), 3 m/s (3rd row) and 5 m/s (bottom). With 1 m/s wind it can be seen that the plume touchdown is inside the plant and that the 1 ppm contour fills a very large area extending a couple of hundred meters upwind of the stack due to gravity effects. One can observe that the wind is not strong enough to push the dense plume uphill, so the office building does not see concentrations near 1 ppm. With 2 m/s wind the plume touches down in front of the hill. No plume develops upwind of the stack, but with the exception of a thin finger of the plume the hill prevents the gas from flowing NE. The concentration around the office building is slightly above 1 ppm. With 3 m/s wind the plume touches down at the hill slope and is transported up and above the hill, with very little gas being deflected back into the plant. Maximum H_2S concentrations above 3 ppm are predicted, which is well above levels of concern, but below legal limits. With 5 m/s wind the plume makes a direct hit at the office building, with concentration around 1 ppm, i.e. more diluted due to stronger winds. With stronger wind the plume hits higher on the building or above, and at concentrations lower than 1 ppm. To conclude for the office building, concentrations above levels of concern can be seen for wind speeds from 2 to 5 m/s from SW, but would never exceed legal limit of 10 ppm.

Inside the plant at ground level problematic gas concentrations can be seen for wind speeds less than 3 m/s. In Figure 2 predicted ground level concentrations are shown for 1 m/s (left) and 2 m/s (right) from SW. For 1 m/s the maximum concentrations inside the plant approach 1%, i.e. the legal limit of 10 ppm H_2S. Local concentrations significantly above 10 ppm were predicted for wind speeds below 1 m/s and also for 1 m/s wind when flow rate is reduced e.g. by a factor of two.

The conclusion of the initial study is that there is a need for measures to reduce the gas concentrations, in particular at ground level inside the plant during low wind conditions. There are a number of possible mitigation measures that could be considered, see Table 2.

Table 2: Some possible mitigation measures

Mitigation measure	Comments
Alarms and evacuation	May need to evacuate plant for hours on quiet days
Increase stack height	
Reduce diameter => Increased flow velocity	Noise concerns, may need to strengthen design
Add fans next to stack	May e.g. be used on quiet days only
Preheating of stack flow	Will increase flow velocity
Premixing with air to dilute	Strengthen design and increase capacity, noise concerns

The alarm and evacuation option requires least work, but may be unsatisfactory for several reasons. As need for maintenance or repairs may be one reason to send gas to the stack, it will be costly and far from optimal if the plant will have to be evacuated for hours or even days in calm weather if repairs are needed. Workers may also feel discomfort by relying on alarms to function.

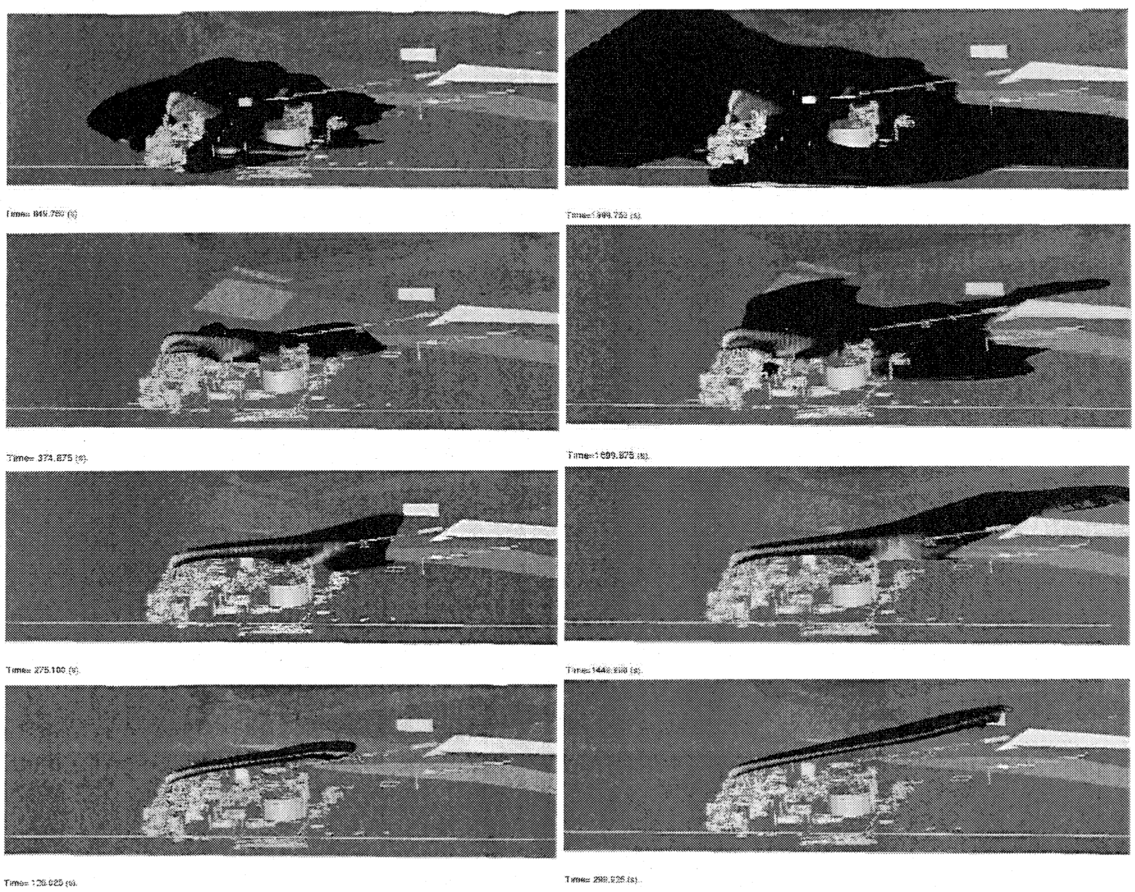

Figure 1: Plume from stack with H_2S concentration above 1 ppm (ACGIH limit) for different wind velocities from SW, 1 m/s (top), 2 m/s (2nd row), 3 m/s (3rd row) and 5 m/s (bottom), the left pictures show plume within a few minutes after start of the release, while the right picture shows the developed plumes.

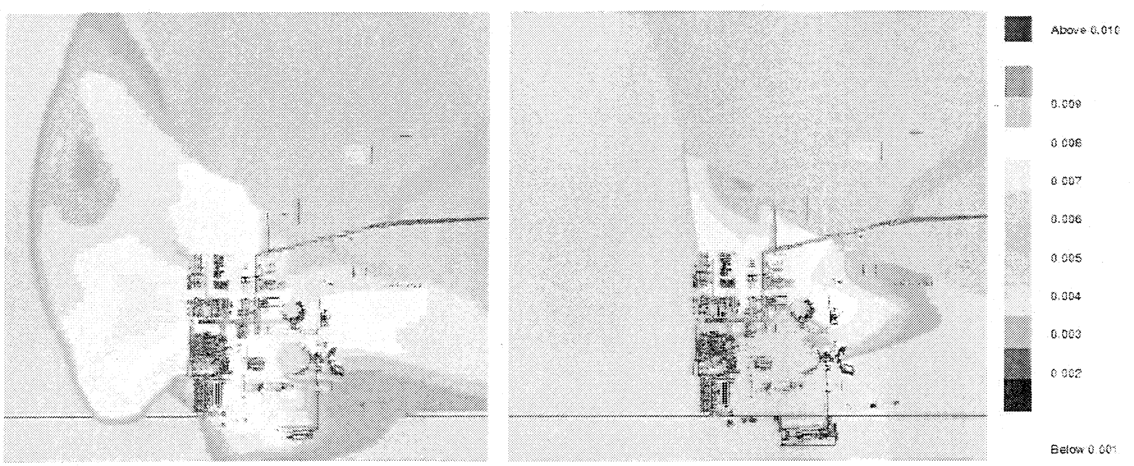

Figure 2: Ground level H_2S concentrations inside plant for 1 m/s wind from SW (left) and 2 m/s from SW (right), concentrations above 1 ppm are shown, maximum concentrations are around 10 ppm (left plot).

To extend the stack height will not be too complicated. With some wind (e.g. > 2 m/s) a significant improvement may be seen, and for this reason Gaussian-based dispersion models may predict a decent mitigation effect. However, for the scenarios of major concern, with no or low wind, a CFD study will demonstrate that only a small reduction in ground level concentrations inside plant can be expected. For the office building on the hill, the worst-case scenario with 3 m/s wind may be somewhat improved, however, another scenario with slightly less wind may give comparable, or even higher, maximum exposure level. The benefits of a certain extension of the stack are therefore limited.

A significant reduction of stack diameter to increase the vertical flow velocity out of the stack gave a significant reduction of exposure for all problem scenarios. The main reasons for the stronger dilution are the enhanced mixing with air due to a higher flow momentum, and the longer (higher) trajectory of the plume before falling to the ground. The implementation of this measure may not be straight-forward as there may be a need to strengthen system design and more oscillations and noise may result

The installation of external fans next to the stack is another option. If properly dimensioned and designed, very good mitigation effects could be seen for all problem scenarios. Benefits with this solution are the external design, i.e. no need to change existing systems, and that it can be activated when needed only (i.e. only during venting at low winds). There may however be noise/vibration issues to consider.

The last two options, preheating of stack flow to reduce density and air injection prior to stack, may be less attractive as significant process modifications may be required. For a gas composition with a density 50% higher than air, it has to be heated 150 K to achieve neutral buoyancy. The heating thus has to be significant relative to 150 K to achieve a significant beneficial effect, which is quite challenging to implement. The air injection prior to stack would strongly increase the flow rate, which could again give challenges with system dimensioning, noise and vibrations. A sensitivity study confirmed a limited mitigation potential with these approaches.

4. Conclusions

A stack dispersion study has been presented. To accurately study stack venting of dense gases it is concluded that validated CFD models using a detailed 3D geometry of a facility as well as surrounding terrain should be applied. During low and no wind scenarios, the vented dense gases may often fall to the ground and lead to an unacceptable environment for workers, with unpleasant odours and/or gas exposure above legal thresholds. Most integral dispersion models frequently used for stack design will not be capable of predicting low wind dispersion of dense gas. Using a CFD model it will be possible to properly analyse the situation by simulating varying wind speeds from different directions to identify the regions where exposure levels may exceed acceptable limits. When required CFD can also be used to identify and properly evaluate ways of mitigation. In the study presented in this article the installation of an external fan next to the stack exit, for use during low or no winds, was concluded to be the best way to mitigate the unwanted gas exposure for workers at the plant.

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