

## Interaction of Steam Curtains with High-Pressure Jets

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In the industrial context, the risk of accidental release to the environment is an event which can occur in different chemical plant areas and cause serious consequences. In the presence of a hazard, risk management involves reducing the probability or the magnitude of the damage without extinguishing the hazard itself. Forms of mitigation can be primary or secondary, according to the target chosen to work on: primary refers to a reduction of the vulnerabilities of the element interested in a possible breakage (for example, hardening the coating of the device), whereas secondary mitigation refers to reduce the effects (consequences around the broken one). Considering the design of the equipment in a state-of-the-art manner, secondary mitigation methods focus on three possible strategies: procedural systems, passive-type systems, and active-type systems.

Passive-type systems are devices designed to confine the leakage to a target area, defend a sensitive area using physical barriers or protect the equipment (such as fireproof coatings in the presence of fuels). Active mitigation systems, on the other hand, exploit the introduction of turbulence in the dispersing cloud, e.g., by adding a fluid to it, and could be successful with gas releases. Among the active mitigation barriers, one of the devices considered is the vapour curtain, but nowadays the understanding of the variables involved in their effectiveness, especially how to manipulate them to achieve the best result, is still not entirely clear.

This work aims to show the efficiency of steam curtains in diluting a high-pressure methane jet by conducting computational fluid dynamics simulations with ANSYS 19.1® software. In doing so, several evaluations were made on the impact that certain operational parameters may have on the efficiency of the system, such as the pressure of the vapour, the position of the vapour curtain along the axis of the release and the amount of the release (obtained varying the diameter of the release).

### 1. Introduction

Industrial operations involving hazardous substances necessitate robust mitigation measures to address the potential risks associated with accidental releases. The frequency of occurrence for failures and leakages of devices is meticulously identified within the industrial process to obtain a comprehensive list of potential hazards. Considering that a compound earns the classification of hazardous if it possesses toxicological or flammable potential, accidental releases pose significant challenges in terms of identification and management and they are often correlated with substantial evolutionary risks, particularly in proximity to residential *neighbourhoods* surrounding industrial plants (Amendola and Contini, 1998). The catastrophic historical events underscore the imperative need for effective mitigation strategies. Examples include the Seveso accident in 1976, the Bhopal gas tragedy in 1984, and the Flixborough explosion in 1974. These incidents inflicted severe environmental damage and human casualties and they are the result of a release of hazardous substances.

Preventative measures (Van't Land, 2018) emphasize the isolation of risk areas, the implementation of control and security alarms, and the establishment of intervention and maintenance procedures as crucial. However, these measures may not suffice in containing potential releases. The lack of flexible protection systems, capable of adapting to variable operational needs, poses a significant challenge in mitigating potential hazards effectively. Given the inherent risks associated with industrial processes involving hazardous substances, the development and implementation of robust mitigation measures, such as the steam curtain, are imperative. By

addressing the complexities of accidental releases and incorporating flexible protection systems, industries can significantly enhance workplace safety, minimize environmental impacts, and mitigate the potential for catastrophic events. The steam curtain, with its adjustable steam pressures and strategic design considerations, emerges as a promising mitigation measure against accidental releases.

Previous research (Diaz-Ovalle et al., 2012; Schoten et al., 2000; Rana et al., 2008; Kulich and Herink, 2022; Lim et al., 2017; Bara and Dusserre, 1997, Marsegan et al., 2016), primarily focused on qualitatively analysing the use of curtains in various settings, with some attention given to pipeline configuration. Specifically, regarding fluids, steam emerges as the most compelling option. A comparison between water and steam underscores the significance of fluid volume rate, with steam requiring less outflow to achieve equivalent dilution. The consensus among these studies suggests that curtains are more effective than passive barriers in promoting gas dispersion, with efficiency correlating with injected fluid flow, generally improving with steam pressure. Considering the design, the shape of the nozzle dictates the appearance of the steam jet (cone, hollow, full, or spray), but nozzle spacing is crucial for efficiency. Optimal spacing strikes a balance between cone jet width and overlap; too wide spacing allows gas to pass through unaffected, while excessive overlap can produce droplets, diminishing system efficiency.

This study aims to validate the above considerations by evaluating the BASF® design in Ludwigshafen am Rhein (Germany) as a reference for a scenario with an accidental release of a methane high-pressure jet. ANSYS Fluent 2019® was used to simulate various scenarios, exploring the impact of two different steam pressures (15 barg and 4 barg), to explore potential advances to improve this technology in the future.

## 2. Material and methods

The maximum extension of the methane jet was considered the one reached by the LFL concentration, which was conservatively assumed as 4.4% mol/mol (Rowley and Bruce-Black, 2012). However, for occupational evaluation, the industry typically adopts the more conservative concentration of half the lower flammability limit (2.2% mol/mol). Hence, this concentration was considered for certain considerations. The simulations were performed using ANSYS Fluent 2019®, employing the  $k-\omega$  SST model within the Reynolds Averaged Navier Stokes formulation (RANS) to incorporate turbulence effects, consistent with prior literature (ANSYS Inc., 2013). The ANSYS® Design Modeler software was employed to meticulously craft the system geometry following specific criteria to ensure stable solutions unaffected by scenario construction. For instance, the domain is extended further in the direction of jet development. The geometry of the system is based on references from the literature (Colombini et al., 2020), where dimensions are proportionate to the equivalent diameter of the methane and steam jet evaluated through Birch's model (Birch et al., 1987). Consequently, its lengths varied based on the dimension of the methane jet considered for the scenario.

The steam curtain is generated through a perforated pipe, powered by pressurized steam, coming from the plant, in case of emergency. Two possible sizes of the hole diameter of the methane jet were assumed in the simulations (as reported in Table 1). The height of the release was established as the one necessary to reach the length of a free jet: it must be considered that the presence of the ground and the steam duct causes the jet to be inclined (Colombini et al., 2020; Colombini et al., 2022). As mentioned above, the configuration for the design investigated in this work was provided by BASF®. In Figure 1, a schematic sizing is reported.

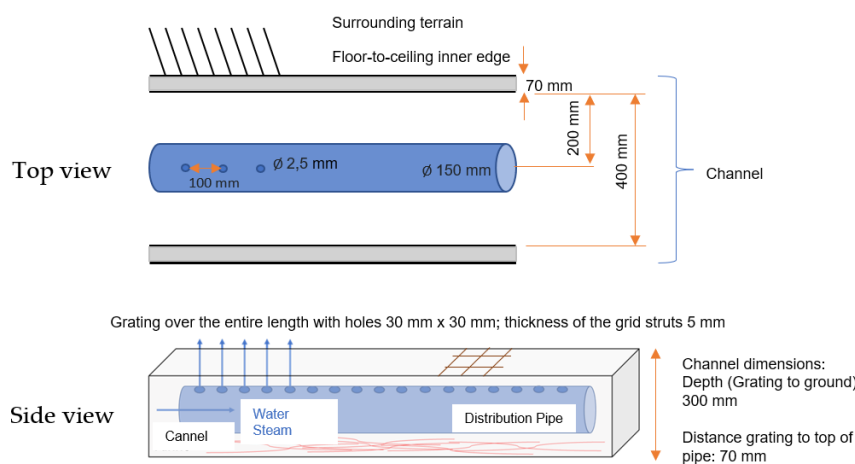


Figure 1: Steam curtain configuration supplied by BASF®.

This kind of mitigation barrier is designed to safeguard vulnerable targets in proximity to the facility, thus, once the maximum possible extension of the methane jet was estimated, the device was positioned at 25, 50 and 75 % of the maximum distance that the jet could travel, to assess a possible optimum distance. Preliminary analysis suggests that the individual emissions do not merge into a plane jet except at significant heights with this configuration (Awbi, 2003). To minimize computational expenses, the simulations only considered 4 holes under the symmetric domain assumption (i.e., 8 holes in the complete domain), since they completely contain the width of the methan jet. The domain together with details about the body lines (e.g., Core, Far1, Far2, etc) used for the sizing of the mesh is sketched in Figure 2a, while a detail of the mesh is shown in Figure 2b. The mesh parameters considered in the simulations are reported in Table 3 (Colombini et al., 2020). A convergence criterion was considered: the energy-related resolution terms should converge to an order of magnitude of  $10^{-6}$ , while for continuity,  $k$ ,  $\omega$ , and velocity along the axis, convergence to a value approximately in the order of  $10^{-3}$  is considered acceptable (ANSYS Inc., 2013).

The main properties of the fluids involved in the evaluation are summed up in Table 1 and Table 2. In the BASF® plants in Ludwigshafen am Rhein, the methane pressure is maintained in a range between 4 and 7.5 bar: to ensure a conservative result, 7.5 bar was therefore assumed in this work as the discharge pressure. Lastly, the wind profile considered within the simulations is assumed exponential with reference speed assumed to be 1 m/s at 10 m height, as the most common in BASF® plants.

Table 1 - Methane properties considered for simulations.

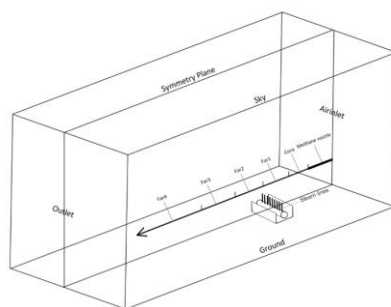
Methane jet real diameter [mm]	Methane jet Birch's diameter [mm]	Storage pressure [bar]	Storage temperature [K]	Mass flow rate [kg/s]
5	8	7.5	293.15	0.02
10	16.1	7.5	293.15	0.09

Table 2 - Steam properties considered for simulations.

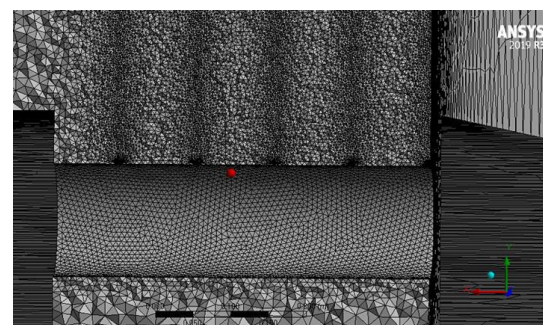
Steam	Steam pressure [bar]	Steam Temperature [K]	Real diameter [mm]	Birch's equivalent diameter [mm]	Flow rate single orifice [kg/s]
SC 4 barg	5	424.85	2.5	3.4	0.0032
SC 15 barg	16	474.46	2.5	5.7	0.0096

Table 3 – Mesh parameters considered.

	Methane Nozzle	Core	Far 1	Far 2	Far 3	Far 4	Steam lines
$\frac{L}{D_{eq}}$ [-]	50	35	35	70	140	390	-
Cell size [m]	0.002	0.008	0.015	0.05	0.05	0.15	0.00025
Growth rate	1.2	1.075	1.1	1.15	1.175	1.2	1.15



a.



b.

Figure 2: a. Schematic representation of the computational domain including the lines of the body of influence method for mesh; b. Mesh details focus on the steam curtain.

### 3. Results

Through Fluent simulations, methane jets can be visualised by creating surfaces defined by a specific methane concentration, in this work assumed as the LFL or the half of the LFL. The assessment only concerns the extent covered along the jet trajectory (i.e., z-axis) as this is the dimension that is intended to be mitigated. An illustration of this can be seen in Figure 3. This enables the measurement of the distance travelled by the chosen iso-concentration surface, providing a clear representation and the establishment of a range within which the steam curtain could be positioned. The results are here reported as a ratio between the maximum extension of the methane jet in the presence of the steam curtain ( $ME_{SC}$ ) and the one without considering the implementation of the device as a methane free jet ( $ME_{FJ}$ ), so as  $\frac{ME_{SC}}{ME_{FJ}}$ . It is crucial to consider this measure with the placement of the vapour barrier. Since it is placed at different distances from the methane inlet, the optimal range of effectiveness varies depending on the individual scenario assessed.

Once a baseline was established, the following simulations, focused on examining the outcomes of various interactions with the steam barrier, were performed. The exploration began by modifying its position and steam pressure to discern which factor has the greatest influence. The vapour pressures under consideration were sourced from BASF®, namely 4 and 15 barg. The placement of the steam curtain was directly linked to the maximum distance covered by the methane jet: options included positioning it at 25%, 50%, or 75% of the maximum distance travelled by the Lower Flammability Limit (LFL) or the half-LFL from the methane outlet.

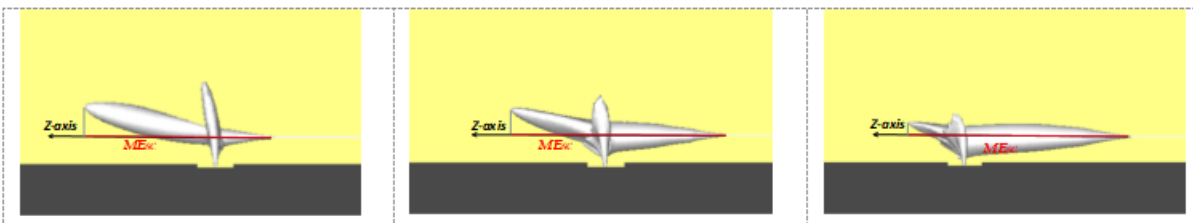


Figure 3: Example of the display results of the isosurface of the methane jet considering a 10 mm diameter (the horizontal jets) with the isosurface of a 15 barg steam curtain (the vertical jets) placed at different positions: from the left, 25%  $ME_{FJ}$ , 50%  $ME_{FJ}$ , 75%  $ME_{FJ}$ .

In Figure 4, the results are summarised in graphs. To simplify the reading, two reference lines were drawn to indicate the ideal dilution result (green line) and total ineffectiveness (red line). In blue and light blue are reported the dilution results for the diameters considered in the study, so 5- and 10- mm. A value close to one indicates the reduction of the effectiveness of the steam curtain since its presence has a negligible influence on the shortening, while the green arrow suggests the trend for an effective curtain.

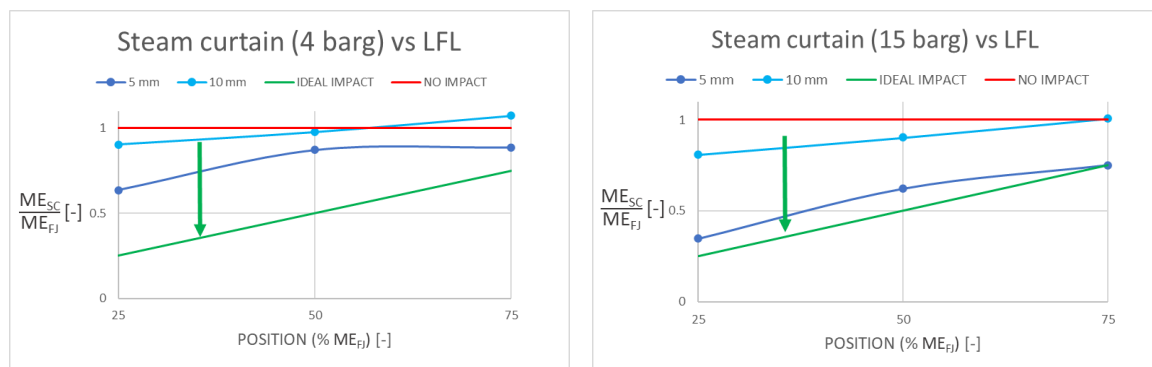


Figure 4: Outcomes from testing the effectiveness of a 4 barg and 15 barg steam curtain against methane jets of 5- and 10-mm diameters, while accounting for Lower Flammability Limit (LFL) concentration and adjusting the positioning.

The primary effect of employing this apparatus is the redirection of the jet upwards, without stopping the methane path: what could be seen is that generally, placing the steam curtain closer to the methane source reduces the length of the jet along its trajectory, but its efficacy improves as it is moved farther away from the source. As

observed in the graphs, the discrepancy between the position of the steam curtain and the maximum distance travelled by the jet diminishes with the increased distance from the methane release point. This phenomenon occurs because the momentum of the jet decreases exponentially with distance.

It is evident from the simulations that increasing steam pressure consistently leads to enhanced jet dilution, but the presence of values greater than one considering the ratio  $\frac{ME_{Sc}}{ME_{Fj}}$  indicates instances where the steam curtain was ineffective or even exacerbated conditions due to inadequate pressure and flowrate for dilution.

Since the half LFL cloud requires a bigger amount of steam to dilute the methane jet, for this case just the 15 barg steam curtain was considered for the results. In this case, the impact of the steam curtain appears to be more pronounced for a 10 mm methane jet compared to a 5 mm one and that lower concentrations are more susceptible to the effects of the steam curtain (Figure 5). This observation can be attributed to the decay of radial velocities within the jet. When considering concentrations below the LFL, the jet expands as the amount of entrained air increases with higher leakage, further reducing the momentum of the methane in the outer layers.

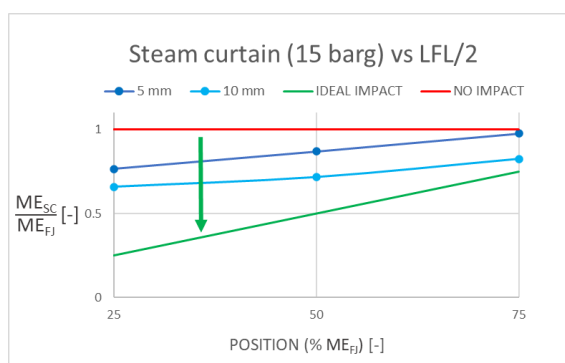


Figure 5: Outcomes from testing the effectiveness of a 4 barg and 15 barg steam curtain against methane jets of 5- and 10-mm diameters, while accounting for half Lower Flammability Limit (half-LFL or LFL/2) concentration and adjusting the positioning.

Since no pressure or position (except one) reached the perfect dilution of the LFL cloud at the point where the steam curtain was placed, these results clearly show the dilution ineffectiveness of the proposed sizing and so all the previous simulations suggest the need for a new proposal for the design.

#### 4. Conclusions

This study helped to qualitatively assess the key factors influencing the effectiveness of using a steam curtain as a mitigation measure for accidental high-pressure methane releases. It identified the crucial variables influencing the effectiveness and penetration of the jet, mainly using the  $\frac{ME_{Sc}}{ME_{Fj}}$  parameter for the analysis.

For individual horizontal methane jets with a diameter of up to 10 mm, simulations were conducted at various heights to establish this minimum, ensuring the absence of ground entrainment effects. The exploration of different positions of the steam curtain along the maximum extent of the methane cloud revealed a greater reduction in length when the curtain was positioned closer to the methane orifice. This proximity to the curtain generally reduces the length of the jet along its axis but increases its effectiveness due to the exponential reduction in jet momentum. The position of the curtain further from the orifice gradually aligned the total distance of the methane jet with the position of the curtain.

The comparison of the Lower Flammability Limit (LFL) and half-LFL concentrations showed a greater distance-decreasing effect as the diameter of the methane leak hole increased for the half-LFL concentrations and this phenomenon could be attributed to the momentum variations associated with the selected concentration area: with smaller concentrations, the exponential decay of radial velocity, coupled with greater air entrainment, resulted in larger methane jets possessing less momentum in the outer layers, consequently affecting a larger portion of the steam jet.

In addition, the different pressures of the steam curtain had a direct impact on the steam flow rate and momentum of the jet, increasing the dilution efficiency with higher pressure. Insufficient pressure, however, could induce certain positions leading to the elongation of the methane cloud.

Analysing the results of this study, several worthy aspects emerge for future investigation, starting with the hole spacing. To obtain a dilution flow rate adequate for the purpose (which varies depending on the positioning of

the curtain), it becomes imperative to explore a new balance between the size and spacing of the holes in the curtain. The configuration proposed by BASF® features relatively wide spacing nozzles, thus highlighting the most critical scenario when the axis of the methane jet aligns exactly with the centre of the spacing nozzle, referred to as a non-coaxial configuration (in which the jet axis remains non-intersecting, generating an optimal challenge). As a result, individual steam jets are unable to generate an aggregate steam flow rate (the so-called plane jet), operating autonomously and thus confining the dilution effect to areas in direct interaction with one or more of these individual jets. Nevertheless, steam openings remain rather small and require high pressures within the pipeline to generate a satisfactory steam flow rate. This leads to future technological advances, suggesting the need to establish a new technical and economic balance. Such an equilibrium would ensure effective dilution of the gas cloud by initially modifying the size of these two components, considering the pressures and flow rates involved in the scenario studied.

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