Journal of Hazardous Materials 298 (2015) 210–220

Contents lists available at ScienceDirect

Journal of Hazardous Materials

journal homepage: www.elsevier.com/locate/jhazmat

Analysis of domino effect in pipelines

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HIGHLIGHTS

- In parallel pipelines domino effect can have a significant influence.
- Domino effect will be originated by jet erosion or jet fire impingement.
- The domino effect probability depends on the geometric arrangement of the system.
- A mathematical model has been developed to estimate domino effect probability.
- This probability allows a more realistic estimation of failure frequencies.

ARTICLE INFO

Article history:
Received 20 February 2015
Received in revised form 14 May 2015
Accepted 18 May 2015
Available online 21 May 2015

Keywords:
Jet impingement
Jet fire
Pipe erosion
Impingement modeling

ABSTRACT

Parallel pipelines are frequently installed over long distances, due to the difficulty in creating or maintaining the required corridor. This implies that a release in one pipeline can seriously affect another one. The main risks associated with this domino effect are erosion by fluid-sand jets and the thermal action of jet fires. In this paper a survey has been performed on the accidents that have occurred, and the diverse associated domino sequences are analyzed. The probability of occurrence of domino effect is a function of the location of the hole, the jet direction and solid angle, the diameter of both pipelines and the distance between them. A mathematical model has been developed to estimate this probability. The model shows how the probability of domino effect decreases with the distance and diameter of the source pipe, and increases with the diameter of the target pipe. Its frequency can be estimated from this probability and from the frequency of the initiating pipe failure plus, in the case of jet fire impingement, the probability of ignition. The frequency of the target pipe failure thus calculated, always higher than its individual frequency, allows a more realistic risk analysis.

1. Introduction

Pipelines are the most important and safe way to transport huge amounts of oil and other fluids to large distances, and to distribute them to the points where they are used. It is a relatively safe system; however, loss of containment events occur from time to time, due to bulldozers, corrosion, aging, landslides, etc. In such cases, a huge amount of flammable material can be released and this can lead to major accidents (i.e., explosions, fires, environmental pollution).

While most accidents have occurred because of the aforementioned causes, in some of them the severity of the event has been increased due to the so-called domino effect [1]. Domino effect can enlarge the scale of an accident and the severity of its consequences. This can be especially important in industrial plants, due to the closeness of the diverse equipment units [2].

In the case of pipelines the situation is essentially different, as usually there are neither vessels nor other units in the near field. However, pipelines lay out over many kilometers crossing the country through forests, rivers and urban zones and, therefore, a hallway must be designed to allow this path. Such a hallway is often difficult to establish and it can be very expensive, and in many cases it is used for more than one pipe. Thus, parallel pipes, sometimes with a short separation between them, transporting gas, oil or water over long distances can be often found. The same situation exists in urban zones, where kilometers of pipes conveying gas, petrol or water are buried, together with other services such as electric wiring. Underground hallways in densely inhabited urban zones have sometimes a dense arrangement of parallel and crossing pipes and utilities, and this implies a certain risk associated to the potential interaction of these systems [3,4].

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http://dx.doi.org/10.1016/j.jhazmat.2015.05.033
0304-3894/

Notation

d	Distance between pipes centers, m
d'	Effective distance, m
D	Pipe diameter, m
D_{eq}	Jet fire equivalent diameter, m
d_{hole}	Hole diameter, m
DN	Nominal diameter, inch or m
$f(A)$	Source pipe failure frequency, m^{-1} $year^{-1}$
$f(B)$, $f(B)_{overall}$	Target pipe failure frequency, m^{-1} $year^{-1}$
$f(B/A)$	Failure frequency of target pipe due to domino effect, m^{-1} $year^{-1}$
L	Jet flames length, m
L_1	Source pipe section delimited by internal and external tangents between both pipes, m
L_2	Source pipe section delimited by the internal tangent between pipes and the line linking their centers, m
P, $P_{domino\,A\rightarrow B}$	Probability of domino effect, -
P_1	Probability that a hole in the source pipe may imply impingement, -
P_2	Probability that a jet from a hole with risk of impingement may reach the target pipe, -
P_2-L_1	Impingement probability of a jet from a hole located in L_1, -
P_2-L_2	Impingement probability of a jet from a hole located in L_2, -
$P_{impingement}$	Probability of jet impingement, -
$P_{iginition}$	Jet ignition probability, -
q	Reduction factor, -
r	Source pipe radius, m
R	Target pipe radius, m
Re	Reynolds number, -
s	Proportion factor -
S	Lift-off, m
u	Velocity at the gas outlet, $m \cdot s^{-1}$
u_{av}	Average jet velocity, $m \cdot s^{-1}$
u_j	Jet velocity at gas outlet, $m \cdot s^{-1}$
Δ	Angle formed by the external tangents of two pipes, delimiting a circular sector at the smallest pipe, rad
α_n	Jet angle jet, rad
β	Half solid angle of jet impingement, rad
δ	Angle delimiting the position of a hole, rad
δ_{L2}	Angle delimiting the position of a hole within L_2, rad
δ_t	Angle giving the intersection between L_1 and L_2, rad
θ	Angle formed by the external tangents of two pipes, delimiting a circular sector at the largest pipe, rad
λ	Angle covering the narrow range that the jet direction may take issuing from a hole in L_1 section, rad
μ	Dynamic viscosity, kg m^{-1} s^{-1}
ρ	Density, kg m^{-3}

In these situations, it is possible that a loss of containment occurred in a pipe affects another close pipe. This has happened in diverse accidents, with severe consequences on people or with environmental impact.

Several authors have assessed the impact of high pressure releases in parallel-running pipelines. Mohsin et al. [5] studied the underground natural gas pipeline safety distances, analyzing the possible outcomes of an accident associated with high-pressure water issuing from a pipe. Mazzola [6] assessed the consequences of high pressure releases of flammable gas from different rupture sizes in two parallel natural gas pipelines. Other authors [7–16] have focused on the metallurgical failure analysis of specific accidents in pipelines, caused by the action of a high-pressure jet issuing from a source pipe and damaging a second one. Wang et al. [17] analyzed the possible domino effect, in the event of the release from a pipeline, associated to thermal radiation, blast and ejected fragments.

However, none of these authors has attempted to develop a model allowing the assessment of how this domino effect can affect the frequency of failure of a given pipelines system. Such a tool would be quite useful for the risk analysis of pipeline transportation systems.

In this paper, a novel approach for the assessment of domino effect in pipelines is developed. Based on a historical survey of pipeline accidents, a mathematical model is proposed to estimate the probability of domino effect in parallel pipelines, aerial or buried, associated to a jet and to the resulting erosion or thermal effects. The model has been applied to two different accidental scenarios.

2. A survey of domino effect accidents in pipelines

After a literature search, eight cases have been found of accidents involving parallel pipes. Accidents occurred in smaller urban pipes have not been included, nor accidents generated by other services (e.g., electrical lines). The available information has been summarized in Table 1.

Natural gas was involved in seven accidents. The source pipeline conveyed water (four cases), natural gas (three cases) or oil (one case). In three cases three pipes were involved. The initial loss of containment in the source pipe was caused by corrosion or sabotage (two cases). Once the first jet of fluid appeared, the time to failure of the target pipe was known in one of the cases (80 min). The distances between both pipes ranged between 6 and 0.05 m.

In three cases the failure of the target pipeline was due to a jet fire from oil (one case) or natural gas (two cases) release. In one of the natural gas jet fire cases, the distance between both pipes was 7.9 m and the time to failure was 20 min.

The features of these cases are essentially different from those found in the domino effect sequences occurred in process/storage plants, even though there can be some coincidence. In the case of plants, a significant number of equipment (vessels, columns, piping...) are located on a relatively reduced area, with rather short separation distances. This means that thermal radiation, overpressure or ejected fragments have a high probability of reaching a vulnerable element, often a vessel. Among the significant differences with respect to the domino accidents in pipelines, the following can be emphasized [1,2]: the main initial causes in plants are mechanical failure and human factor, while the contribution of corrosion (quite important in pipelines) is very low; furthermore, only 10% of the initiating events occurred in on-plant pipes and associated valves. However, an aspect is relatively similar in both systems: the influence of external events, which in plants constitutes 30% of initiating events, while in pipelines third party activities (often excavating machinery) reaches approximately 38%.

3. Domino effect possibilities

Once a first release occurs, the possible domino effect can follow diverse sequences.

If there is a hole in a pressurized pipe, the fluid will be released at a very high velocity. In the case of a gas, if $P_{pipe}/P_{outside} > 1.9$ the gas will exit at the sound velocity; for liquids or two-phase flow the velocity will be lower. This may have serious effects on other neighboring pipes, associated to erosion and thermal impact. However, the situation will depend on whether the pipelines are aerial or buried. Another important aspect is whether the fluid is