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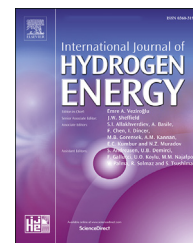
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Quantitative risk analysis of a hazardous jet fire event for hydrogen transport in natural gas transmission pipelines

H.A.J. Froeling^a, M.T. Dröge^b, G.F. Nane^{c,*}, A.J.M. Van Wijk^a^a Mechanical, Maritime and Materials Engineering, Delft University of Technology, The Netherlands^b N.V. Nederlandse Gasunie, The Netherlands^c Electrical Engineering, Mathematics and Computer Science, Delft University of Technology, The Netherlands

HIGHLIGHTS

- Enhanced flame descriptions and near field radiation levels are provided
- Comprehensive mathematical transformations of the geometric view factor are proposed
- Hydrogen failures have low and swift declining lethality levels compared to methane
- IR is the risk calculated for multiple failures cumulated for weather scenarios

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ABSTRACT

With the advent of large-scale application of hydrogen, transportation becomes crucial. Reusing the existing natural gas transmission system could serve as catalyst for the future hydrogen economy. However, a risk analysis of hydrogen transmission in existing pipelines is essential for the deployment of the new energy carrier. This paper focuses on the individual risk (IR) associated with a hazardous hydrogen jet fire and compares it with the natural gas case. The risk analysis adopts a detailed flame model and state of the art computational software, to provide an enhanced physical description of flame characteristics.

This analysis concludes that hydrogen jet fires yield lower lethality levels, that decrease faster with distance than natural gas jet fires. Consequently, for large pipelines, hydrogen transmission is accompanied by significant lower IR. However, ignition effects increasingly dominate the IR for decreasing pipeline diameters and cause hydrogen transmission to yield increased IR in the vicinity of the pipeline when compared to natural gas.

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* Corresponding author.

E-mail addresses: h.froeling@outlook.com (H.A.J. Froeling), m.t.droge@gasunie.nl (M.T. Dröge), g.f.nane@tudelft.nl (G.F. Nane), a.j.m.vanwijk@tudelft.nl (A.J.M. Van Wijk).

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Introduction

Hydrogen is considered one of the key factors in the impending required changes in the energy system transition. The reuse of the existing natural gas system could serve as a catalyst for entering in the upcoming hydrogen economy. Nevertheless, due to its characteristics, hydrogen is perceived as being more dangerous.

The Netherlands was one of the first countries to start with a regulation on safety concerning transportation of hazardous substances. Already in the seventies, the Dutch Committee on the Prevention of Disasters published the early versions of the Coloured Books, that provide guidelines for safety requirements and calculation methodologies for the transport of hazardous substances through pipelines. Central to the safety of pipeline transport is external safety, that refers to the risks to which “external parties” are exposed as a result of pipeline transport activities. A relevant risk metric is the individual risk (IR), that is defined as the probability of a fatal injury per year of a hypothetical individual who is continuously present at a particular distance from the pipeline [38,46].

Currently, there is still limited adequate knowledge of the involved risks when reusing the natural gas transmission network for hydrogen transport. Authors of [20] and [14] explored the adverse consequences of hydrogen transmission associated with an accidental pipeline failure. The European NaturalHy project analyses the consequences of pipeline failure for hydrogen up to 24% in methane/hydrogen mixtures [32]. The author of [39] presents the influence of operating pressure and pipeline diameter on the consequences of hydrogen up to 50% in methane/hydrogen mixtures. The authors of [33] and [44] determine the consequences and the IR for hydrogen up to 100% in methane/hydrogen mixtures.

Aforementioned research uses prescribed software to determine the thermal radiation of jet fires and does not give any physical explanation of the outcomes. Others use point source models to calculate the thermal radiation levels. While the point source model is elegant by its simplicity, it should be recognised that point source models incorrectly predict the thermal radiation in the vicinity of the flame (typically within two flame lengths) where the radiation is heavily influenced by the flame geometry [29]. Some enhancement is possible by considering the flame represented by multiple point sources along the length of the flame [32]. More accurate results, especially in the near field, can be obtained by taking the flame characteristics into account by the solid flame model [9,35].

To obtain a better view of the practical risks involved for hydrogen jet fires, the IR is calculated for multiple failure events along the pipeline cumulated for various wind scenarios and compared to the natural gas case. Based on the pipeline characteristics and the transmission gas, the probability of occurrence of a jet fire and the associated consequence will be calculated. The vulnerability model will be used to determine the lethal effect of the thermal radiation assuming 20 s of exposure of constant radiation. The solid flame model is used to get accurate radiation levels, even in the vicinity of the pipeline, where the flame geometry heavily

influences the level of radiation. This work utilises SAFETI-NL v8.21 [10], state of the art software, to provide an enhanced physical description of flame characteristics, taking into account the tilting effects due to the prevailing wind conditions. Mathematical transformations are specified to apply the solid flame model for tilted flames.

Risk methodology

Risk is the combination of the probability of pipeline failure and the adverse consequence of failure. Not all failures result in severe consequences, and two types of pipeline failure, namely, a leak or rupture, can be distinguished. For underground natural gas as well as for hydrogen transmission, the contribution of leaks to the final risk is negligibly small, and pipeline ruptures dominate the risk, considered as only relevant failure scenario [15,32]. Following a rupture of an underground pipeline a sphere-shaped gas cloud is formed due to the instantaneous release of large quantities of expanding gas. If ignited, a fireball is observed, which rises and burns out, followed by a high momentum jet fire which gradually reduces in height with time due to decreasing internal pressure [32]. Following the Dutch Decree on the External Safety of Pipelines (Bevb) the consequence of failure will entail the modelling of the jet fire only [36].

To determine the risk from an accidental pipeline rupture, it is essential to distinguish the two sorts of effects: over-pressure due to physical explosion and thermal radiation of the jet fire. Generally, over-pressure effects are not high enough to make a significant contribution to the risk, and thermal radiation dominates the risk [15]. No significant over-pressure is measured for hydrogen releases [2]. Therefore, in this work, thermal radiation is considered as the only relevant consequence scenario.

Individual risk

The individual risk (IR) is a common criterion worldwide to quantify the spatial risks of pipeline transport. IR is the probability of a person dying as a result of a pipeline operation. In the Netherlands, the location-specific risk (LSR) is used, that slightly differs from the IR. The LSR is defined as the probability in a per-year basis of a hypothetical unprotected person who is continuously present at a certain distance from the pipeline dying as a result of pipeline operation [38,46]. In contrast to the IR, the LSR does not assume flight behaviour and the person is continuously present. In the paper the wording IR is used, while actually the Dutch LSR is meant.

An analysis of the IR entails the quantification of the risk along an imaginary line perpendicular to the pipeline, referred to as a risk transect. In scientific research, the IR is frequently determined from a single failure event located at the origin of the risk transect, although pipeline failure could occur at any point along the pipeline. Failures which are located further away from an individual result in less significant radiation levels than failures nearby. Thus, IR calculation from a single failure location results in an overestimation of the risks for

gases with small effect distances, for instance, hydrogen. Ideally, the IR should be calculated by integrating the risk associated with each failure event over the pipeline length that could potentially lead to a lethality level of at least 1% at that particular location [6].

The paper focuses on a quantitative risk analysis for a hazardous jet fire event, for which the IR will be quantified. The IR is the product of the failure frequency, ignition probability and the lethality, summed over the rupture locations on the pipeline. The failure frequency and the ignition probability may vary due to different design conditions along the pipeline length. By assuming uniform design conditions, and thus uniform failure frequency and ignition probability along the pipeline length, the IR can be estimated by the following equation:

$$IR = FF \cdot P_i \cdot \int_0^b L_t(y) dy \quad (1)$$

where: FF —failure frequency in 1/km·year, P_i —probability of ignition, $L_t(y)$ —lethality due to thermal radiation obtained from an incident at position y on the pipeline, b —length of the pipeline section in m.

Generally, the lethality drops with distance from the flame due to decreasing radiation levels. Therefore, the IR is calculated for all distances in the vicinity of the pipeline. To obtain insight into the practical risks involved, the IR should be cumulated for all weather scenarios [43]. Wind conditions are usually uncertain; they may have various velocity and be from any direction. In this work, sixteen wind scenarios are used: four wind velocities of 1.5, 3, 5, and 9 m/s [36], then uniformly distributed over four wind directions of 0°, 90°, 180° and 270°, with respect to the risk transect.

$$IR(d) = FF \cdot P_i \cdot \int_0^b \left(\sum_{u_w} \sum_{\varphi_w} L_t(u_w, \varphi_w, d, y) / 16 \right) dy \quad (2)$$

$$u_w \in \{1.5, 3, 5, 9\}, \varphi_w \in \{0^\circ, 90^\circ, 180^\circ, 270^\circ\}$$

where u_w is the wind velocity in m/s, φ_w the wind direction in degrees (with respect to the risk transect) and d the distance from the jet fire.

For numerical calculations, the IR can be modelled by the summation of multiple discrete failures at specific locations. The mutual distance between the discrete failures should be low enough to ensure that the IR does not change significantly when the mutual distance is decreased. An acceptable starting distance is 10 m.

For numerical calculations, the IR can be modelled by the summation of multiple discrete failures at specific locations. The mutual distance between the discrete failures should be low enough to ensure that the IR does not change significantly when the mutual distance is decreased. An acceptable starting distance is 10 m [36].

Frequency of jet fire

The probability of a hazardous jet fire happening is the combination of the failure frequency and the ignition probability. The failure frequency defines the number of failures per year,

usually expressed with the unit ‘(failures) per km per year’ [21]. For natural gas transmission pipelines, the failure frequency is reported by the European Gas Pipeline Incident Data Group (EGIG), consisting of pipeline data of seventeen natural gas transmission system operators in Europe. In the literature, there is no clarity on what failure frequencies to use for hydrogen transmission in existing natural gas pipelines. No casuistry exists for hydrogen transmission in natural gas pipelines specific and there ought to be looked for suitable data from a comparable system [42], for which the natural gas case seems to be applicable.

Gas release resulting from a pipeline failure is prone to ignition. How likely the ignition of an accidental gas release to occur is a critical factor in determining the risk associated with pipeline transport of flammable gases, such as natural gas and hydrogen. The ignition probability is, therefore, a key input when undertaking risk analysis and the value selected is a direct multiplier of the IR calculated [1]. There is no thorough clarity about the cause of ignition of flammable gas release from an underground pipeline. Typically, the probability of ignition assigned is established on an analysis of historical accident data [33].

Failure frequency

The are several failure mechanisms that could cause pipeline failure. The main mechanisms that cause failure of natural gas transmission pipelines in Europe are corrosion, external interference, mechanical defects, ground movement and others [11]. Most of these failure causes are independent of the transmission content [17]. The contribution of each failure threat to the failure probability of the pipeline should be aggregated. The failure frequency is proportionate with the cumulative failure probability of the individual causes, assumed all threats occur independently with very small failure probability [31]:

$$FF \propto \sum_c P(F_c) \quad (3)$$

where the subscript c denotes the cause of failure and $P(F_c)$ is the probability of failure associated with the failure scenario c .

A difference between natural gas and hydrogen relates to hydrogen embrittlement, that could potentially increase the probability of mechanical failure, that accounted for less than 15% of the failures of natural gas transmission in the period 1997–2016 [11]. Hydrogen embrittlement is a degradation of the steel of the pipeline due to hydrogen. The influence of the different forms of hydrogen embrittlement are studied in the NaturalHy project; the only relevant form of hydrogen embrittlement for carbon steel is fatigue crack growth [34]. Fatigue crack growth can be managed by controlling the pressure swings that occur in the pipeline. As the crack growth rate is well known [19] and generally the number and size of pressure swings in transmission pipelines are reasonably low, it is, therefore, assumed in this paper that hydrogen pipelines will not fail due to hydrogen embrittlement.

Assuming hydrogen transport will be operated under strict conditions (i.e. pressure-swings are controlled properly) as for natural gas transmission, hydrogen transport in existing natural gas transmission pipelines will face similar failure

frequencies as natural gas transport. Hence, it is appropriate to use historical natural gas data for hydrogen transmission.

Ignition probability

Incident data for natural gas transmission pipelines indicate that the probability of ignition generally increases for increasing diameter and pressure of the pipeline [24]. Authors of [3] present a correlation derived from statistical analysis and show that the ignition probability of natural gas releases increases linearly with the operating pressure and the pipeline diameter squared, presented in Eq. (4). Having multiple possible mechanisms, the two credible mechanisms that were considered most probable acting as an ignition source and causing ignition are frictional sparks, i.e. rocks striking together, created during the significant impact of pipeline failure and electrostatic discharge [3]. The probability of ignition is given by:

$$P_i = 0.0555 + 0.0137 \cdot p \phi^2 \quad (4)$$

in which p is the operating pressure in bar and ϕ the pipeline diameter in m.

For hydrogen release from underground pipelines, it is not clear what ignition probability should apply since there is little historical data available. Hydrogen has a minimum ignition energy (MIE)¹ of only 0.017 mJ [28], causing hydrogen-air mixtures to be extremely easy to ignite, for which a static spark may already suffice. As a comparison, Dutch low-caloric natural gas has a MIE of 0.31 mJ [4], and requires slightly more energy to ignite and weak ignition sources will not be of sufficient energy. A low MIE suggests that the gas is more likely to ignite than a gas with higher MIE due to a wider range of suitable ignition sources [16]. However, sources citing ignition probability values for hydrogen releases are not available, to the authors best knowledge, so it is conservative to assume the probability of ignition for hydrogen equals 1.

Consequence of jet fire

Thermal radiation

This work uses the solid flame model, developed by Ref. [7], to calculate the thermal radiation exposed to the observer. Following the model, the thermal radiation at a given location is calculated based on the approach that merely the visible surface of the flame contributes to the thermal radiation, and can be solved by the product of a geometric view factor the flame emissive power at the surface and the atmospheric transmissivity of radiation through the intervening atmosphere [9]. This is expressed by:

$$q'' = F_g Q_s \tau_a \quad (5)$$

where: q'' —thermal radiation at a given location in kW/m², F_g —geometric view factor, Q_s —flame emissive power at the surface in kW/m², τ_a —transmissivity of radiation through the intervening atmosphere.

The atmospheric transmissivity is the fraction of thermal radiation passing unabsorbed atmosphere before it reaches

the individual, and it drops with distance from the flame. Appendix A1 presents its mathematical expression. The solid flame model has the necessary complexity to define flame dimensions to determine the surface emissive power and view factor of the flame [30].

Surface emissive power

The emissive power at the flame surface (Q_s) can be solved with the fraction of the heat radiated from the flame surface and the flame emissive power released from the combustion of the flammable gas. The flame emissive power is defined by the mass release rate, the combustion energy and the total surface area of the flame. This is expressed by Ref. [7]:

$$Q_s = F_s \left(\frac{\dot{m} H_c}{S} \right) \quad (6)$$

$$F_s = 0.11 + 0.21 e^{-0.00323 u_j} \quad (7)$$

where: F_s —fraction of the heat radiated from the flame surface, \dot{m} —mass release rate in kg/s, H_c —combustion energy in J/kg, S —surface area of the flame in m², u_j —jet outflow velocity after atmospheric pressure in m/s. Eq. (7) only applies to gases with a molecular weight less than 21 g/mol, such as natural gas or hydrogen.

Generally, elaborated software can be used to calculate the release conditions (i.e. mass release rate and exit velocity) at post-expansion conditions and determine the flame characteristics (i.e. shape and dimensions). In this work, SAFETI-NL v8.21 software is utilised.

The solid flame model assumes the jet fire emits thermal radiation uniformly and stationary from the flame surface. For jet fires under stationary conditions, the burning rate is equal to the mass outflow rate of the flammable gas [5,40].

For hydrocarbon releases, the amount of soot has a considerable influence on the heat radiation [23]. For natural gas jet fires, the combustion process is relatively efficient and produces little soot [5,27].

Geometric view factor

The view factor (F_g) describes the geometric relationship between the flame and person exposed to the flame. The calculation of the view factor has the complexity that it is necessary to define flame shape and dimensions [30]. The calculation for realistic flames, taking into account the tilting effects due to the prevailing wind conditions, is quite complicated. In practice, a simplified flame shape is used [22,27]. Fig. 1A illustrates the jet fire being simplified as a truncated cone. Jet fires are usually considered as a tilted cylinder with a diameter equal to the average of the widths of the two end discs of the truncated cone [5,40].

The author of [29]² provides a method to determine the geometrical view factor of a cylinder with an angle θ , illustrated in Fig. 1B. The method begins with the calculation of supporting variables a and b , characterised by the length of the flame, the distance from the centre of the bottom plane of a flame to the object, and the radius of the cylinder. The tilt of the flame (with respect to the vertical) is taken positive

¹ The minimum ignition energy is the least energy required to enable combustion [37].

² Note, the view factors for cylindrical flames in Eq. (6.A.14)–(6.A.17) of [40], describing the view factors of [29], are incorrect.

downwind. Substitutions are made to simplify view factor equations.

$$\begin{aligned} a &= l/R \\ b &= d/R \end{aligned}$$

(8)

$$F_g = \begin{cases} \sqrt{F_{ah}^2 + F_{av}^2}, & \varphi_w \in \{0^\circ, 180^\circ\} \\ \sqrt{F_{ch}^2 + F_{cv}^2}, & \varphi_w \in \{90^\circ, 270^\circ\} \end{cases} \quad (14)$$

$$\pi F_{ah} = \tan^{-1}\left(\frac{1}{G}\right) - \left(\frac{a^2 + (b+1)^2 - 2(b+1 + ab \sin \theta)}{AB}\right) \tan^{-1}\left(\frac{AG}{B}\right) + \frac{\sin \theta}{C} \tan^{-1}\left(\frac{(ab-K)K}{C\sqrt{b^2-1}}\right) \quad (9)$$

$$\pi F_{av} = -I \left(\tan^{-1}(G) - \frac{a^2 + (b+1)^2 - 2b(1 + a \sin \theta)}{AB} \tan^{-1}\left(\frac{AG}{B}\right) \right) + \frac{\cos \theta}{C} \tan^{-1}\left(\frac{(ab-K)K}{C\sqrt{b^2-1}}\right) \quad (10)$$

$$\pi F_{ch} = \tan^{-1}(G) - \frac{(a^2 + b^2 - 1) \tan^{-1}\left(\frac{EM}{T}\right)}{2T} + \frac{\sqrt{b^2-1} \sin \theta}{2D} \left(\tan^{-1}\left(\frac{U}{V}\right) - 2 \tan^{-1}\left(\frac{\sin \theta}{D}\right) \right) \quad (11)$$

$$\pi F_{cv} = -J \left(\tan^{-1}(G) - \frac{(a^2 + b^2 + 1) \tan^{-1}\left(\frac{EM}{T}\right)}{2T} \right) + \frac{\cos \theta}{2D} \tan^{-1}(UV) - \frac{Q}{2} \ln \left(\frac{a^2 + b^2 - 1 - N}{a^2 + b^2 - 1 + N} \right) \quad (12)$$

with

$$\begin{aligned} A &= \sqrt{a^2 + (b+1)^2 - 2a(b+1) \sin \theta} & K &= (b^2 - 1) \sin \theta \\ B &= \sqrt{a^2 + (b-1)^2 - 2a(b-1) \sin \theta} & M &= a^2 + (b+1)^2 \sqrt{(b-1)/(b+1)} - 2a \sin \theta \\ C &= \sqrt{1 + (b^2 - 1) \cos^2 \theta} & N &= (2a\sqrt{b^2-1} \sin \theta)/b \\ D &= \sqrt{b^2 - \sin^2 \theta} & Q &= a^2 \sin \theta \cos \theta / 2(a^2 \sin^2 \theta + b^2) \\ E &= a^2 + (b+1)^2 \sqrt{(b-1)/(b+1)} - 2a \sin \theta & T &= \sqrt{(a^2 + b^2 + 1)^2 - 4(b^2 + a^2 \sin^2 \theta)} \\ G &= \sqrt{(b-1)/(b+1)} & U &= (ab/\sqrt{b^2-1} + \sin \theta) / \sqrt{b^2 - \sin^2 \theta} \\ I &= (a \cos \theta) / (b - a \sin \theta) & V &= (ab/\sqrt{b^2-1} - \sin \theta) / \sqrt{b^2 - \sin^2 \theta} \end{aligned} \quad (13)$$

where: l —length of the flame in m, R —radius of the cylinder in m, d —distance from the centre of the bottom plane of a flame to the object in m, θ —angle of the flame with respect to the vertical.

The geometrical view factor at a certain distance is the geometric mean of the view factor of the vertical and horizontal flame area [25], given by the vectorial sum of the horizontal and vertical view factors. The horizontal and vertical view factors stated above are given for the along wind (up- and downwind) and crosswind situation. For along wind conditions, the individual is assumed to be located in line with the wind direction. Crosswind conditions correspond to an individual located perpendicular to the direction of tilt. The horizontal and vertical view factors are influenced by the wind from a specific direction φ , causing a rotation in the horizontal plane. For instance, θ' becomes negative in the near field of the flame and for upwind conditions. The wind direction φ_w rotates 90° counter-clockwise a full revolution around failure location, $\varphi_w = 0$ corresponds to downwind conditions. Tilt angle θ is taken positive if the risk transect is located downwind. The geometrical view factor (F_g) of a flame becomes:

where F_{ah} and F_{av} represent the horizontal and vertical geometrical view factor for along wind conditions, respectively. F_{ch} and F_{cv} are the horizontal and vertical geometrical view factor for cross wind conditions, respectively. Variable φ_w represents the wind direction with respect to the risk transect in degrees.

Mathematical transformations

The expression of the view factors in Ref. [29] are derived for a flame without lift-off. A flame lift-off is causing a rotation in the vertical plane that changes the angle under which the individual observes the flame, illustrated by Fig. 1C. Also, in this work, the risk is aggregated for multiple failure along the pipeline length; hence the view factors should be determined for various failure location. Transformations are required to take into account the lift-off and tilt of the flame and adjusted distance of the individual to the location of failure.

Eq. (15) presents the transformations required, which are valid for an initially vertical outflow. The distance from the centre of a lifted flame base to a person is given by the

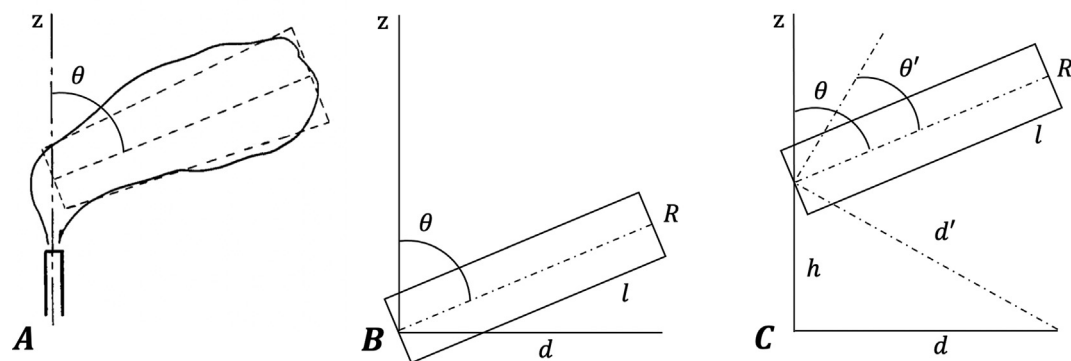


Fig. 1 – (A) Typical jet fire geometry for tilted flames considering the wind effects, approximated by a simplified cylindrical crone [9], in accordance with the flames illustrated in Ref. [26]. Jet fire flames represented as cylinders with average radius R , flame length l , and d as the distance from the centre of the flame base (without lift-off) to a person, all influential parameters for view factor calculation. (B) Flame with tilt angle θ , exclusive of any lift-off. (C) Flame with initially vertical outflow including a specific lift-off h considering wind effects, for which transformations are required.

Pythagorean theorem, based on the distance from the centre of a flame base without lift-off and the distance of the location of failure on the pipeline to the origin of the risk transect. The tilt angle for a lifted flame (i.e. the angle between the centre-line of a lifted-off flame and the plane between the centre of the bottom of the lifted-off flame and an individual at distance d), is calculated by geometry, using the angle of the flame with respect to the vertical, the lift-off and the distance from the centre of a flame base without lift-off.

$$d' = \sqrt{d^2 + h^2 + y^2} \quad (15)$$

$$\theta' = \theta - \tan^{-1}(h/d)$$

where: d' —distance from the centre of a lifted flame base to an individual, d —distance from the centre of a flame base without lift-off in m, h —jet fire lift-off height in m, y —failure location in m, θ' —tilt angle of lifted-off jet fire in degrees, θ —tilt angle of jet fire without lift-off in degrees.

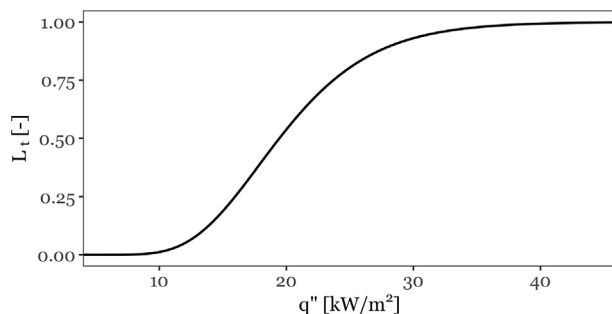


Fig. 2 – The relationship between the lethality and level of radiation, assuming 20 s exposure of a time-average outflow, using the vulnerability model [12,36]. The probability of a fatal injury is half for thermal radiation of 19.5 kW/m^2 . A lethality of 0.9 corresponds to the thermal radiation of 28.3 kW/m^2 , and radiation levels lower than 9.8 kW/m^2 could be deemed insignificant.

Lethality

Lethality encloses the probability of a fatal injury caused by the thermal radiation of a hazardous jet fire. The lethality can be determined using the vulnerability model, developed by Ref. [12]. Following the Dutch Decree on the External Safety of Pipelines (Bevb), the lethality is determined based on 20 s of exposure, using a time-average outflow over the first 20 s and therefore, constant heat radiation [36]. The vulnerability model is described in Appendix A2. Fig. 2 characterises the dose-effect relationship resulting from thermal radiation.

Risk analysis

The IR associated with hydrogen transportation through underground transmission pipelines will be calculated and compared to the natural gas case. Transmission pipelines have various diameters; the representative diameter of 16"

Table 1 – Mass outflow and exit velocity after atmospheric expansions for jet fires, calculated with SAFETI-NL v8.21. These release conditions are independent on the wind conditions and specified for hydrogen and natural gas (H_2/NG), released from a 16" and 36" pipeline with an initial pressure of 66 bar. Based on the release conditions, the release power, i.e. the product of the mass outflow and the net calorific value, and the fraction of heat radiated at the flame surface, are determined.

Scenario	\dot{m}	u_j	$\dot{m}H_c$	F_s
16"	224.6/969.9	192.0/85.7	27.4/48.5	0.23/0.27
36"	1815.1/6468.5	485.1/201.9	221.4/323.4	0.16/0.21

where: \dot{m} —mass outflow in kg/s, u_j —exit velocity in m/s, H_c —net calorific value, ($\dot{m}H_c$)—release power in GW, F_s —fraction of heat radiated at the flame surface.

Table 2 – The flame characteristics calculated with SAFETI-NL v8.21, specified for hydrogen and natural gas (H₂/NG), released from a 16" and 36" pipeline with an initial pressure of 66 bar. Also, the flame characteristics are influenced by the wind forces and, therefore, specified for four additional scenarios where the wind velocity is defined in m/s. Based on the flame characteristics, the flame surface area (using the flame length and the two widths of the truncated cone) and the surface emissive power of the flame (using Eq. (6)) are calculated.

Scenario		l	\bar{w}	h	θ	S	Q_s
16"	1.5 m/s	163.2 / 238.6	37.5 / 70.5	34.2 / 40.7	4.0 / 8.0	22.3 / 61.8	272 / 235
	3 m/s	140.3 / 208.8	34.9 / 66.4	24.9 / 25.2	8.1 / 15.9	18.1 / 51.6	336 / 281
	5 m/s	125.7 / 188.7	33.3 / 60.3	18.1 / 15.2	13.5 / 25.3	15.6 / 42.8	388 / 339
	9 m/s	118.5 / 176.6	32.2 / 50.7	11.6 / 7.3	24.5 / 35.2	14.5 / 34.2	419 / 424
36"	1.5 m/s	327.9 / 472.2	69.7 / 126.5	76.0 / 99.8	2.1 / 4.1	82.9 / 216.5	351 / 363
	3 m/s	277.9 / 405.5	63.0 / 118.3	59.8 / 73.1	4.0 / 8.3	63.8 / 175.7	456 / 447
	5 m/s	245.5 / 363.0	59.1 / 112.7	48.0 / 53.5	7.0 / 13.8	53.1 / 151.3	547 / 520
	9 m/s	228.0 / 342.1	58.3 / 109.3	37.1 / 35.1	12.6 / 24.8	49.2 / 139.8	590 / 562

where: l —flame length in m, \bar{w} —average width of the flame in m, h —flame lift-off in m, θ —flame angle (with respect to the vertical) in degrees, S —flame surface area in 10^3 m^2 , Q_s —surface emissive power of the flame in kW/m^2 .

and 36" have been adopted to determine the IR. The operating pressure of both hydrogen and natural gas transport has been set to the design pressure of the pipeline, that is typically 66 bar in the Netherlands. This is also a standard pressure for the European natural gas transmission pipelines [11].

The risk analysis uses SAFETI-NL v8.21 to calculate the release conditions and the flame characteristics (i.e. flame shape and dimensions), considering the influence of prevailing wind conditions. An analysis related to the view factor, thermal radiation and lethality for a gas release from a 36" pipeline is performed. Next, the IR is determined for both pipeline diameters, including several wind directions and multiple potential failure locations.

Release conditions

The mass outflow rate and the exit velocity are crucial variables for the flame characteristics of jet fires, referred to as release conditions. Both the release conditions and the characteristics of the flame after ignition are determined with SAFETI-NL v8.21. At first, the software calculates the depressurisation and expansion of released gas from initial conditions to the final conditions at atmospheric pressure [45], based on the work of [13]. Gas outflow from ruptures of underground pipelines is accompanied by the formation of a crater, affecting the air intake and outflow speed of the released gas [15]. SAFETI-NL v8.21 has the addition of crater formation model, developed by Ref. [8], and an improved method of modelling expansion to atmospheric pressure, for calculating the specific air intake and the reduced outflow velocity based on the properties of the gas released [41]. The mass flow and exit velocity after expansion to atmospheric pressure are presented in Table 1. Both quantities are average values over the first 20 s.

Hydrogen releases have, on average, a mass outflow rate of around 1/4 of the mass outflow of natural gas. Consequently, hydrogen releases have less significant outflow powers relative to natural gas, even though hydrogen has a higher energy content per unit of mass (the net calorific values for natural gas is 50.0 MJ/kg and 122 MJ/kg for hydrogen). Despite hydrogen's lower mass outflow rate, its outflow velocity is more

extensive than natural gas, due to the low density of hydrogen. Table 1 indicates that hydrogen releases have outflow velocities more than twice as high as the outflow velocities of natural gas. This reduces the fraction of heat radiated from the flame surface significantly, especially for massive gas releases.

Flame characteristics

The flame characteristics calculated for different weather conditions assuming stationary situations can be found in Table 2 and are displayed in Fig. 3 for wind speeds of 1.5 and 9 m/s. Due to the larger outflow velocity, hydrogen flames are less affected by the wind speed, reflected by a smaller flame angle, as depicted in Eq. (A6). The tilt of hydrogen flames is roughly half the tilt of natural gas flames. Also, hydrogen jet fires have smaller flame dimensions than natural gas jet fires, due to its less significant outflow velocity and more considerable buoyancy³. Appendix A3 gives a physical explanation for different tilt angles for natural gas and hydrogen jet fires.

The surface emissive power is inversely proportional to the surface area, as discussed in Eq. (6). As a result, hydrogen releases will have a slight increase in surface emissive power when compared to natural gas releases, despite having a significantly reduced outflow power.

Single failure event

Fig. 4 illustrates the view factor, thermal radiation and lethality for a single failure event, based on the release conditions and flame characteristics mentioned above. The results are calculated for various distances⁴ from a gas release from a 36" pipeline assuming downwind.

Hydrogen jet fires have lower view factors compared to natural gas, since hydrogen releases are accompanied with smaller flame dimensions with lower tilt angles. Consequently, hydrogen flames have less surface emissive power

³ Tendency to go upwards. Considering atmospheric air having a density of 10°C is 1.2 kg/m^3 , the relative density to air of hydrogen and natural gas is, respectively, 0.068 and 0.74.

⁴ Calculations are made with distances larger than 45 m to obey the restriction $b > 1$ in Eq. (8).

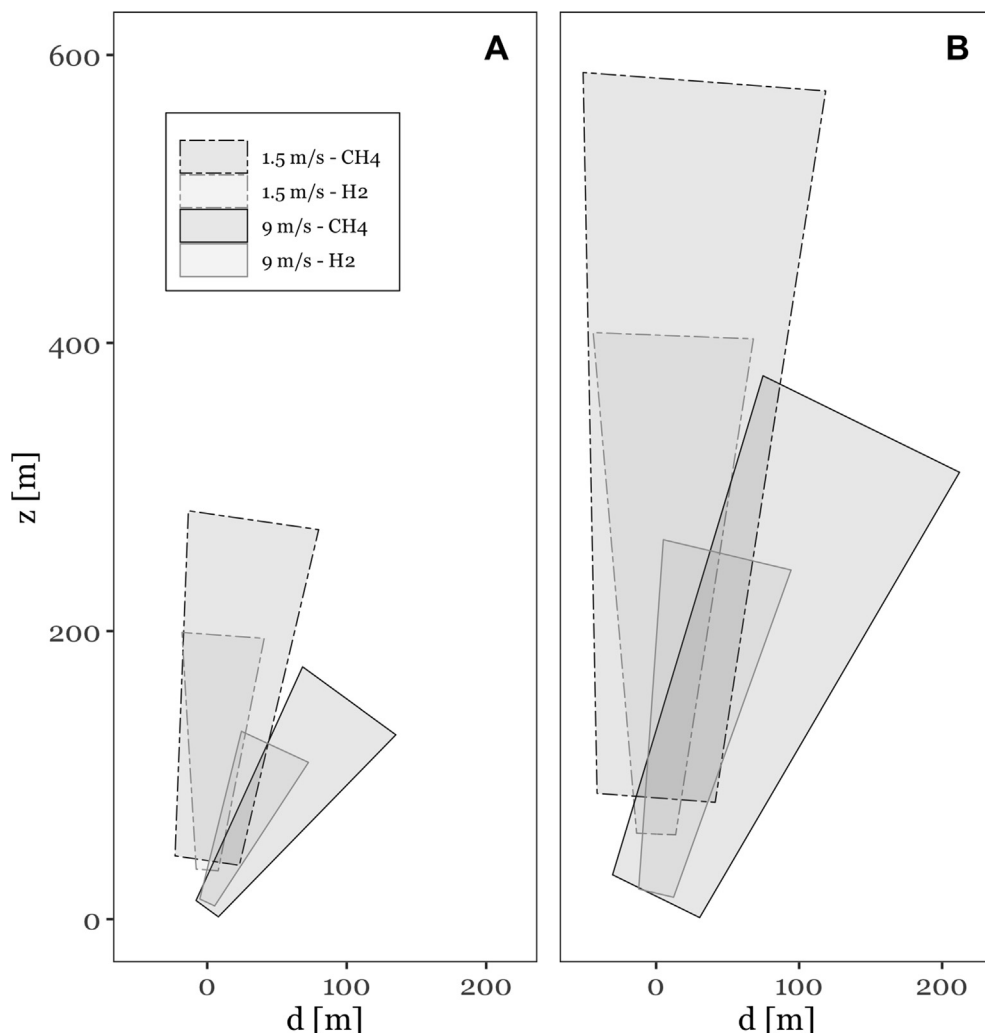


Fig. 3 – Two-dimensional jet fire representations of gas releases from (A) 16" pipelines and (B) 36" pipelines, conveying natural gas (CH₄) and hydrogen (H₂), considering wind velocities of 1.5 m/s and 9 m/s. Three-dimensional flames modelled as a truncated cone are calculated with SAFETI-NL v8.21.

contributing to the overall thermal radiation. The thermal radiation generally drops with increasing distances due to decreasing view factors and increasing absorption of radiation by the atmosphere before it reaches a person at a distance d . Also, the wind direction has a considerable influence on the distribution of thermal radiation.

An individual experiences lower thermal radiation levels for hydrogen releases than natural gas releases, especially in the vicinity of the failure. In the vicinity of the pipeline failure, all scenarios have a lethality level above 0.5. At further distances away from the pipeline failure, the wind effects do not have a considerable influence on the thermal radiation and predominantly affected by the surface emissive power.

The lethality for hydrogen releases decreases much faster with distance than for natural gas releases. For hydrogen, a significant impact is to be expected up to 350 m from the pipeline failure. For natural gas, this is more than 600 m from the failure.

Individual risk

The IR is the product of the failure frequency, ignition probability and lethality, that is cumulated for all wind scenarios and multiple failures locations along the pipeline. The lethality at a specific location differs for each wind scenario and failure locations along the pipeline. To determine the IR for both pipeline diameters, Fig. 5A illustrates the lethality cumulated for all wind scenarios and multiple discrete failures locations with a mutual distance of 20 m. The first thing to notice is that lower lethality levels accompany hydrogen releases compared to natural gas due to hydrogen's lower thermal radiation levels. The difference between the lethality levels increases with distance since the lethality of hydrogen releases decreases much faster with distance than it does for natural gas. This phenomenon also explains hydrogen's reduced lethality at short distances since discrete failure events further away from the risk transect have less effect on a person.

Fig. 5B illustrates the IR for both pipeline diameters. The rupture failure frequency for natural gas transmission is obtained from the European Gas Pipeline Incident Data Group (EGIG) database consisting of pipeline data of seventeen natural gas transmission system operators in Europe for the period 1997–2016. The failure frequencies are respectively $1.7 \cdot 10^{-5}/\text{year}$ and $4 \cdot 10^{-6}/\text{year}$ for a 16" and 36" pipeline of 1 km [11], applicable for both natural gas and hydrogen transport in

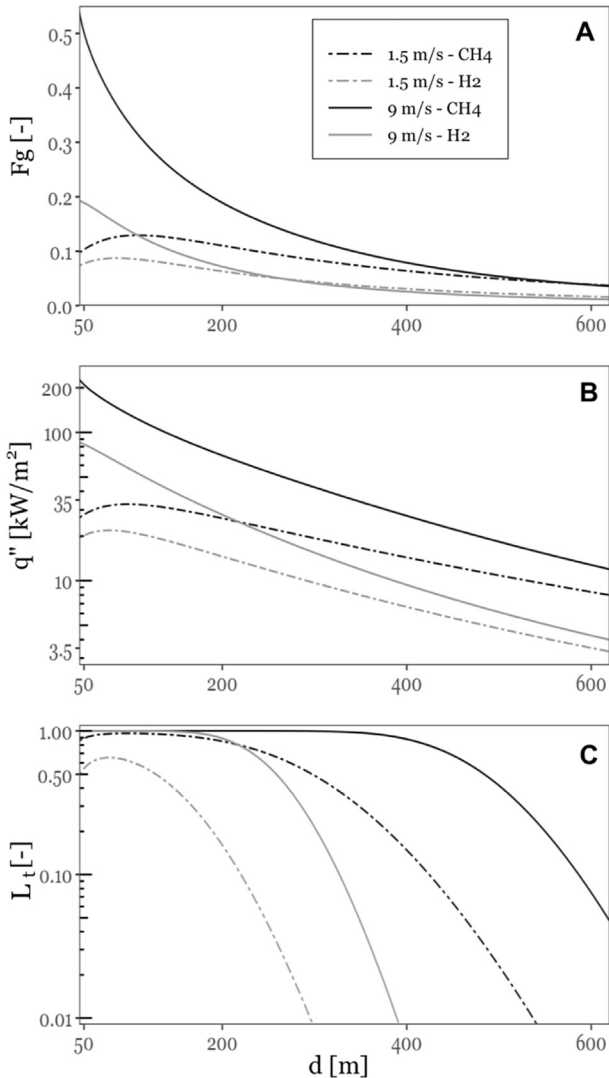


Fig. 4 – Comparison of (A) the geometrical view factor, (B) thermal radiation, and (C) lethality, associated with a single failure event ($y = 0$) from a 36" pipeline, conveying natural gas (CH₄) and hydrogen (H₂). The wind velocity is 1.5 m/s and 9 m/s, considering downwind conditions ($\phi_w = 0^\circ$). The geometrical view factor (F_g) describes the proportion of the flame surface exposed to the person at a distance d from the pipeline. The thermal radiation (q'') of a jet fire is the product of the geometric view factor, the flame emissive power at the surface and the transmissivity of radiation through the intervening atmosphere, defined by Eq. (5) for solid flames. The lethality caused by thermal radiation (L_t) is solved by the probit relation illustrated in Fig. 2, that characterises the dose-effect relationship.

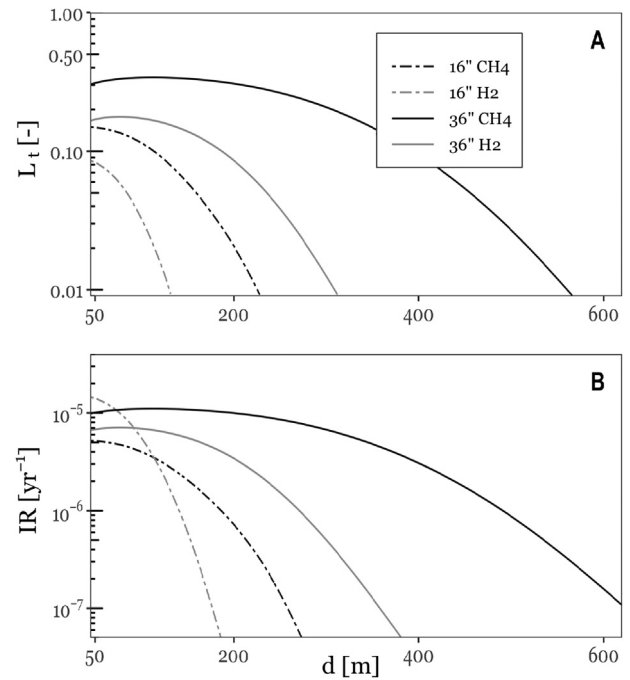


Fig. 5 – Analysis of the lethality (A) and individual risk (B) corresponding to a 16" pipeline and a 36" pipeline, conveying natural gas (CH₄) and hydrogen (H₂). The individual risk (IR), being the product of the failure frequency, ignition probability and the lethality summed over all scenario's, is the probability of a fatal injury per year of a hypothetical individual who is continuously present at a certain location near the pipeline. The lethality (L_t) is the probability of a fatality caused by a potential pipeline failure. To determine the IR, the lethality is calculated by the summation of discrete failure events distributed along the pipeline cumulated for all weather scenarios.

existing underground natural gas pipelines. Using Eq. (4), the probability of ignition for natural gas releases is respectively 0.20 and 0.81 for a 16" and 36" pipeline, operating at 66 bar. The probability of ignition for hydrogen releases is unity regardless of the pipeline diameter and operating pressure.

Fig. 5B shows that the pipeline diameter has a considerable influence when comparing the IR for hydrogen and natural gas transmission. For a 36" pipeline, hydrogen transmission is accompanied by lower individual risk values than natural gas transmission, even though it has an increased probability of ignition. Also, the IR for hydrogen transmission decreases faster with distance than for the natural gas case. Hydrogen's lethality levels are relatively lower than its increase in the probability of ignition compared to natural gas, especially at more considerable distances. However, for a 16" pipeline, hydrogen transmission is accompanied by a significant increase in IR at distances close to the pipeline. Although the lethality levels are roughly reduced by a factor two; the increase in ignition probability by a factor 5 causes a higher risk in the vicinity of the pipeline. The IR for hydrogen transmission decreases

faster with the distance. It is calculated to be lower from approximately 90 m for a 16" pipeline compared to the natural gas case.

Conclusion

This paper presents the individual risk (IR) associated with a hazardous hydrogen jet fire, cumulated for multiple failure events along the pipeline and various wind scenarios. Also, this work adopts the solid flame model and state of the art computational software, to provide an enhanced physical description of flame characteristics for accurate thermal radiation level, even in the near field.

The results indicate that hydrogen releases are associated with lower lethality levels, that decreases much faster with distance compared to those of natural gas releases. The ignition effects have an enormous influence when comparing the risk for hydrogen and natural gas transmission, and increasingly dominate the IR for decreasing pipeline diameters. For 16" pipelines, hydrogen transmission has an increase in IR in the vicinity of the pipeline compared to natural gas. However, at further distances, the IR is predominantly affected by the lethality, which steeply reduces with distance for hydrogen transmission. For 36" pipelines, hydrogen transmission is accompanied with significantly lower IR than natural gas transmission. Here, the reduces lethality dominates the increased probability of ignition.

To further improve the present analysis, it could be suggested that results were validated with experimental measurements. The solid flame model assumes a jet fire that emits thermal radiation uniformly and stationary from the surface. However, the values of emissive power are also dependent on the surface area of the flame and reduce with time due to decreasing internal pressure. Hence the values of emissive power used will not necessarily agree with experimentally measured thermal radiation from flames.

The next step of the present study can be research of the ignition probability of hydrogen releases from underground high-pressure pipelines. For the IR, the probability of ignition is an essential parameter, but for hydrogen a relatively unambiguous parameter. In this work, the ignition probability for hydrogen releases is assigned with the conservative value of unity. Probable reduction of hydrogen's ignition probability will inevitably result in lower IR values.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

A1. Transmissivity

The atmospheric transmissivity is the fraction of thermal radiation passing unabsorbed atmosphere before it reaches the individual at distance dependent upon the amount of water vapour in the air and the distance from the flame [40]:

$$\tau_a = 2.02(P_w \bar{H}d)^{-0.09} \quad (A1)$$

where P_w is vapour pressure of the saturated water in N/m^2 and \bar{H} is the relative humidity. A saturated vapour pressure of water as 1705 N/m^2 [40], corresponding to an average temperature of 10°C , and a typical Dutch relative humidity of 0.765 [45], transmissivity can be expressed with distance from the flame to the location of the individual using the following equation:

$$\tau_a = 1.06d^{-0.09} \quad (A2)$$

A2. Vulnerability model

The vulnerability model uses the probit relationship; the lethality is the probability of probit Pr being larger than a stochastic variable with a normal distribution ($\mu = 5$, $\sigma = 1$), expressed as:

$$L = \Phi(Pr - 5) \quad (A3)$$

where Φ is the cumulative standard normal distribution. Variable Pr is the Probit, that characterises the dose-effect relationship resulting from thermal radiation, expressed as

$$Pr(d) = -12.8 + 2.56 \ln \left(\int_{t_0}^{t_1} q''(t, d)^{(4/3)} dt \right) \quad (A4)$$

in which the time-dependent thermal radiation q'' in kW/m^2 experienced by a person at a distance d from the flame, and $t_1 - t_0$ is the duration of exposure in seconds [36].

Following the Dutch Decree on the External Safety of Pipelines (Bevb), the lethality is determined based on 20 s of exposure, using a time-average outflow over the first 20 s and therefore, constant heat radiation [36]. Considering a stationary discharge with an exposure time of 20 s, the probit can be simplified to Eq. (A5)

$$Pr(d) = -9.80 + 3.41 \ln(q''(d)) \quad (A5)$$

A3. Tilt angle

Jet fires are resulting from an ignited flammable gas released with considerable momentum [5]. An essential and relatively simple parameter for the tilt of the flame is the dimensionless wind to jet velocity ratio R_w , expressed in Eq. (A6). For low R_w the flame is jet-driven and predominately characterised by the jet velocity. For increasing R_w the flame becomes increasingly influenced by wind and dominated by wind forces [18].

$$R_w = u_w / u_j \quad (A6)$$

where u_w is the wind velocity and u_j the jet velocity, both with the unit m/s.

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