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Science of the Total Environment 951 (2024) 175444

Contents lists available at ScienceDirect

Science of the Total Environment

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

Review of techniques, challenges, and gaps in the subsurface gas release knowledge base

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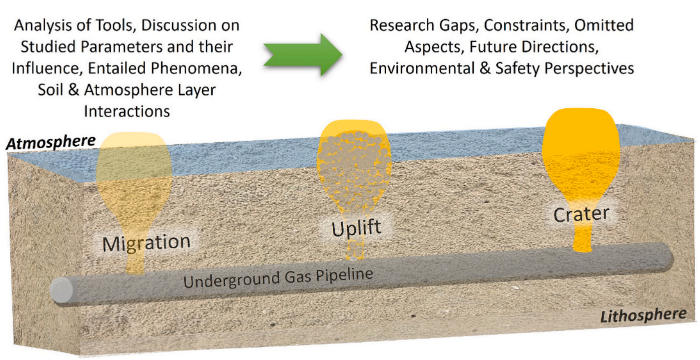
HIGHLIGHTS

- Provide an overview of current research on underground gas releases including numerical and experimental work.
- Highlight the extensive understanding of migration through numerical tools, and of crater using empirical formulations.
- Emphasize the integration of spout-fluidization processes and detection techniques into the underground gas release field.
- Highlight the main literature gap of identifying and bridging various underground gas flow regimes.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Pavlos Kassomenos

Keywords:
Buried pipeline
Flow regimes
Underground
Gas leakage
Computational
Experimental

ABSTRACT

Underground pipelines serve as critical infrastructure for gas transmission, strategically buried for safety, environmental, and economic considerations. Despite their importance, operational challenges and external interferences can lead to underground gas leaks with potentially catastrophic consequences for both human safety and the environment. The presence of a protective soil bed introduces complexities in understanding subsurface transport phenomena and quantifying gas releases accurately. Herein, this review presents a systematic analysis of published research in the field of underground gas releases, with an emphasis on interdisciplinary approaches that connect the lithosphere and atmosphere. The analysis highlights the broad spectrum of employed methods, including theoretical models based on fundamental principles, empirical formulations derived from experimental data, and sophisticated computational tools. A clear fundamental understanding and computational analysis, and to a lesser extent experimental, have been established to describe the migration regime. In contrast, more empirical research has addressed the crater formation regime, though focus was given to the far-field modelling following the soil ejection rather than the transient phenomena leading to the formation of the crater. Additionally, this review touches upon practical and conceptual topics, such as detection and localization techniques, and flow regimes in other gaseous flows through soil and powder beds, putting into question the applicability of some presumed granulated concepts to the flowing behavior expected beyond migration. The research landscape predominantly focuses on investigating the influence of release parameters on the release phenomena only from the atmospheric or soil domain perspective. This work provides insights that aim to first transcend both domains and then bridge the three distinct flow regimes—migration, uplift, and crater

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https://doi.org/10.1016/j.scitotenv.2024.175444
Received 19 May 2024; Received in revised form 2 August 2024; Accepted 9 August 2024
Available online 10 August 2024

formation—despite the limited acknowledgment of the necessity of addressing all regimes concurrently through a universal approach. This review serves as a valuable resource for engineers to develop innovative solutions for the management of risks associated with underground gas leaks.

1. Introduction

The worldwide production of natural gas increased from 1249 billion cubic meters in 1974 to around 4014 billion cubic meters in 2020 (IEA, 2022) as a result of an increase in demand for all energy sources. Currently, as the focus toward lower-carbon energy resources is emerging, natural gas' consumption is expected to rise for its low environmental impact as compared to other fossil fuels and its emergence as a cleaner fuel (Neumann and Von Hirschhausen, 2015). However, the hazards associated with the production and transportation of natural gas shadow the benefits associated with its branding as a preferred fuel because of its flammability (methane LFL: 5 %) and more potent, than carbon dioxide, contribution to the greenhouse effect (Lelieveld et al., 2005). Herein, the focus is on underground transportation with buried pipelines, which are prone to leakage mainly due to corrosion and external interferences (Zhang and Weng, 2020), because of the potentially severe consequences including injuries, loss of life, environmental and economic losses, as shown in Table 1.

The control of the risks associated with underground gas releases requires an in-depth understanding of the release mechanism and its dispersion into the atmosphere. Depending on the release and flow conditions, underground gas releases result in an underground gas flow regime ranging from migration, to uplift, to crater formation (Fig. 1).

Table 1
Examples of major incidents involving underground natural gas pipelines releases.

Event	Cause	Consequences	Reference
Natural Gas Pipeline Rupture and Fire, Carlsbad, New Mexico 19 August 2000	Internal corrosion	• 15.54 m wide and 34.44 m long crater • Upward jet fire (30 min) • 12 fatalities • $ US 1 million losses	(NTSB, 2003)
Rupture and ignition of a gas pipeline, Ghislenghien, Belgium, 30 July 2004	Previous external mechanical aggression	• 10 m diameter x 4 m deep crater • Gas explosion followed by an upward jet fire, secondary gas leaks • 24 fatalities, 132 injuries • €100 M losses • Properties destruction over 200 m radius	(French Ministry for Sustainable Development (No. 27681), 2009)
Pipeline rupture at Gas Authority India Limited (GAIL), Andhra Pradesh, India, 27 June 2014	Overpressurized gas supply + internal corrosion (inappropriate use of wet natural gas)	• Initial blast of the pipeline formed a 14 m diameter crater • Unconfined Vapor Cloud Explosion and jet fire • 23 fatalities, 40 injuries • Significant environmental and economic losses	(Lakshmi and Kumar, 2015; Mishra and Wehrstedt, 2015)

The main categorization of the regimes has been established by Houssin-Agbomson et al. (2018) who optically classified them as uplift, mixed situation, and crater formation. Bonnaud et al. (2018) later added migration at the lower-end and distinguished uplift between low uplift and strong uplift; leading to four regimes including crater formation. In brief, a low uplift occurs when the evacuation of the gas is not intense enough to form a crater; but rather results in cracks of variable size, and an elevation of the ground. The intensity of the uplift depends on the release conditions and can be classified as strong when the uplift is accompanied by a partial or unsteady crater formation. A crater is formed when the soil is expelled, a gap is formed on the ground surface and the gas is released as a free jet. In principle, a higher release pressure would favor crater formation. Other favorable conditions, but not limited to, are sandy soil over clayey soil and an upward release orientation.

Significant attempts have been made to enhance the understanding of the release mechanisms (Acton et al., 2010b; Yan et al., 2015; Bonnaud et al., 2018; Ebrahimi-Moghadam et al., 2018; Srour et al., 2022; Zhu et al., 2023). However, the acquired knowledge has not been systematically analyzed beyond what has already been suggested in the established literature (Van den Bosch and Weterings, 2005). In particular, related to a comprehensive methodology for the characterization of the release out of an underground pipeline hole and the prediction of the associated gas release rate. The current industry practice is to evaluate the consequences through an *unobstructed* release model modified by reducing the jet impulse to account for the soil layer (Stoffen, 2005). The unobstructed gas release is a common fluid dynamic's problem that has extensively been studied (Batchelor, 2000) and documented in the process safety literature (Lees, 2012). All this, despite the equally extensive literature on fluidized and spouted beds which stresses the effects of the soil layer on the flow kinematics.

Herein, this review presents and analyzes the state of the art in underground gas releases from buried pipelines and identifies the gaps in information necessary to develop a universal approach for underground gas releases. While the focus is on natural gas, however, literature addressing other gases is included depending on the relevancy. In many cases, such as the underground gas release regimes, the nature of the released gas does not play a critical role (Bonnaud et al., 2018; Houssin-Agbomson et al., 2018).

2. Methodology

The topic of gas releases from buried pipelines relates to multiple categories of the scientific literature. Consequently, it becomes challenging to identify and highlight the ones contributing and shaping the state-of-the-art toward the objectives of this work; which signifies even more its importance. Therefore, this review has two main sections. Section 3 is the core of the analysis and elaborates on the studies focusing on the release mechanism and the factors affecting the evolution of the transport phenomena. It is broken down into multiple subsections, each addressing the various challenges and questions of this topic rather than grouping them simply based on tools. Many more studies, than the ones listed in Section 3, claim relation to the central topic of this work, and came up during the search. Instead of discarding them entirely, Section 4 presents a summary of some indicative studies and groups them into three main subthemes: fluidization, spout-fluid beds, and detection/localization of leaks from buried pipelines, noting that each one of them could have been or has been the central theme of another review. As one of the main outcomes of the analysis herein, Section 5 brings forward the progress toward a universal approach encompassing the underground gas release and what is required to achieve it.

The following paragraphs in this section provide the details of the search tools and criteria employed in collecting and selecting the related studies. The studies are listed and categorized in Appendix B based on the topic, classification and journal.

After assessing the various search engines and the main sources of information, the Scopus search engine (by Elsevier B.V.) was selected with Google Scholar (by Alphabet Inc.) and Texas A&M University Libraries serving as secondary engines. Among the various keywords and combinations explored, the following three Boolean search queries, applied on the titles, abstracts, and keywords yielded the largest portion of studies: "gas AND (release OR leak OR leakage) AND (buried OR underground) AND pipeline", "rupture AND (buried OR underground) AND pipeline AND gas", and "spout-fluid OR spout-fluidized AND bed" with 770, 136, and 361 studies respectively. Based on their titles, the first level of screening discarded irrelevant, and non-English papers.

Examples of irrelevant papers are those focusing on: a) risk assessment evaluation including but not limited to: leak causes, leak modes, failure frequency, accidents causes and accident probability (mainly studied by Bayesian networks), emergency response planning following incidents; b) pipeline failure by analysis of stress, wall-thinning, corrosion rate, active faults, soil-pipe interactions, and the effect of natural disasters on the pipeline and ground (such as earthquakes); c) gas pipelines in underground tunnels or coal mines; d) underwater pipelines; e) liquid releases (e.g. from water or oil pipelines); and f) soil contamination.

In addition to natural gas, which is the most common gas in the identified studies, other hydrocarbons and hydrogen gas have been included herein. On the other hand, few publications on carbon dioxide release were excluded as its behavior is considered outside the scope of this work, i.e., because of the phase changes that occur and the ductile-brittle behavior transition of the pipe material (Mazzoldi et al., 2008; Ahmad et al., 2015; Mahgerefteh et al., 2016; Yan et al., 2016). Noteworthy, a similar phenomenon was observed for high pressure natural gas pipelines with freezing occurring next to the release point in the soil (Jiao et al., 2014; Zhou et al., 2014; Bonnaud et al., 2018).

Finally, the preceding systematic use of the search engines was complemented by a snowball search (backward in time) to include cited work in the reference list of the selected studies, and (forward in time) to include publications that cite the selected studies.

Based on the presented search criteria, >122 studies (see Table B1, Appendix B) have been reviewed and analyzed, revealing an ascending trend in the yearly number of publications (Fig. 2). This indicates that more efforts are being directed toward understanding the presented topics. Moreover, this potentially implies that effective methods/formulations are being extracted from literature to address the underground gas release hazard.

The initial statement on the very wide breadth of the topic (Murvay and Silea, 2012; Sutkar et al., 2013; Hu et al., 2021b; Korlapati et al., 2022) and the diversity in the selected keywords are further supported by the scattering of (96) words, each repeated at least three times, across the titles of the collected studies (Fig. 3). Moreover, the collected studies are divided across 55 different journals and 22 conferences, with 12 journals hosting up to two studies and just 5 journals hosting more than that. The picture becomes clearer when focusing solely on underground gas release studies (Fig. 4) which are mostly concentrated in few journals (mainly in the Journal of Loss Prevention in the Process Industries (7), Process Safety and Environmental Protection (8), and Journal of Natural Gas Science and Engineering (7)).

It is noteworthy that the underground gas release studies occupy the majority (~ 70 %) of the conferences and the category entitled others. The high number of conferences is mainly attributed to the high industrial application character of the theme and the large number of experimental/empirical formulations, while the category "others" reflects the scattering of the studies, even for the more focused underground gas release topic.

Furthermore, it is clear by the number of publications that some research groups have been quite active in this domain. Table 2 lists the authors (representing a group) who have been engaged in more than one publication as primary author. For the underground gas release studies, a few of the most active authors are Acton and Lowesmith for investigating crater formation (152 and 281 citations, respectively) and Deepagoda for evaluating the subsurface and surface effects on gas migration (87 citations). Other noteworthy studies are of Mason and Sleep, scoring a collective of 1711 and 307 citations, respectively, on

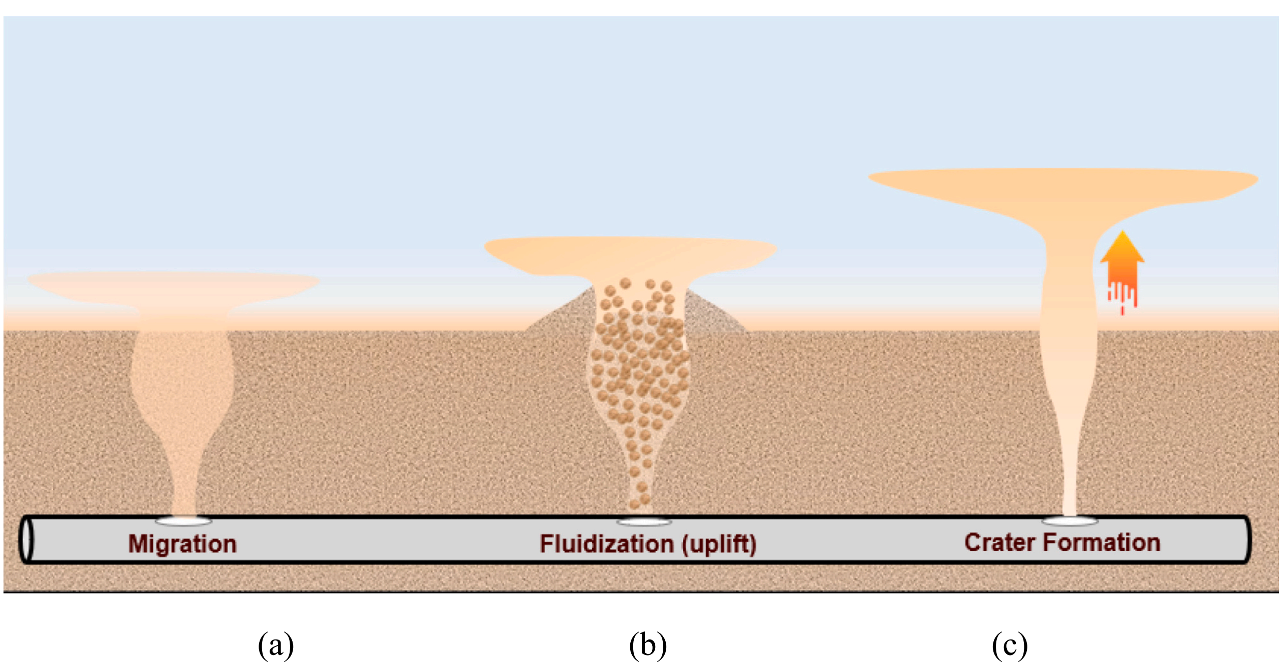

Fig. 1. Underground gas flow regimes: (a) migration, (b) uplift, and (c) crater formation.

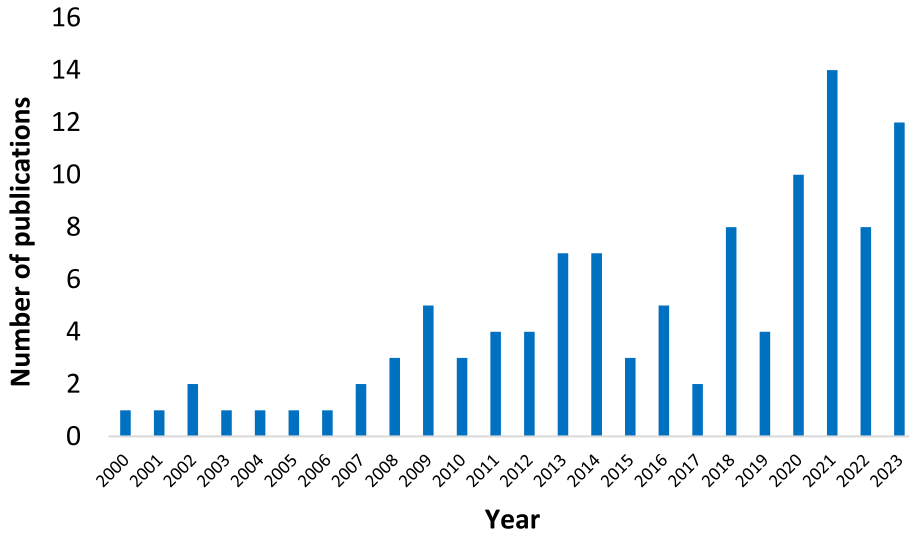

Fig. 2. Annual variation in the number of the selected publications since the year 2000.

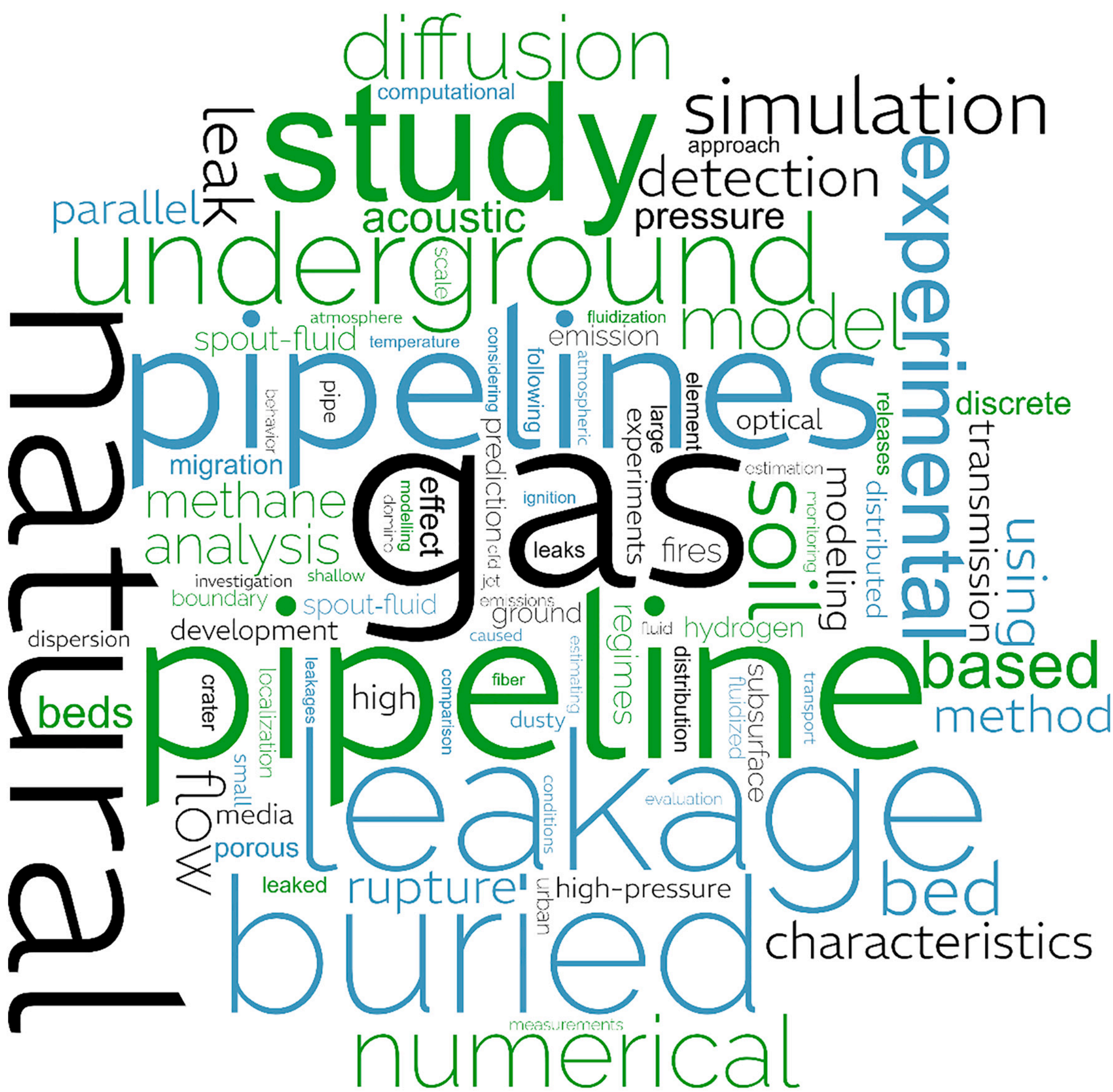

Fig. 3. World cloud based on the titles of the collected studies with the size of each word representing its frequency of appearance. The diagram was made with WordClouds.

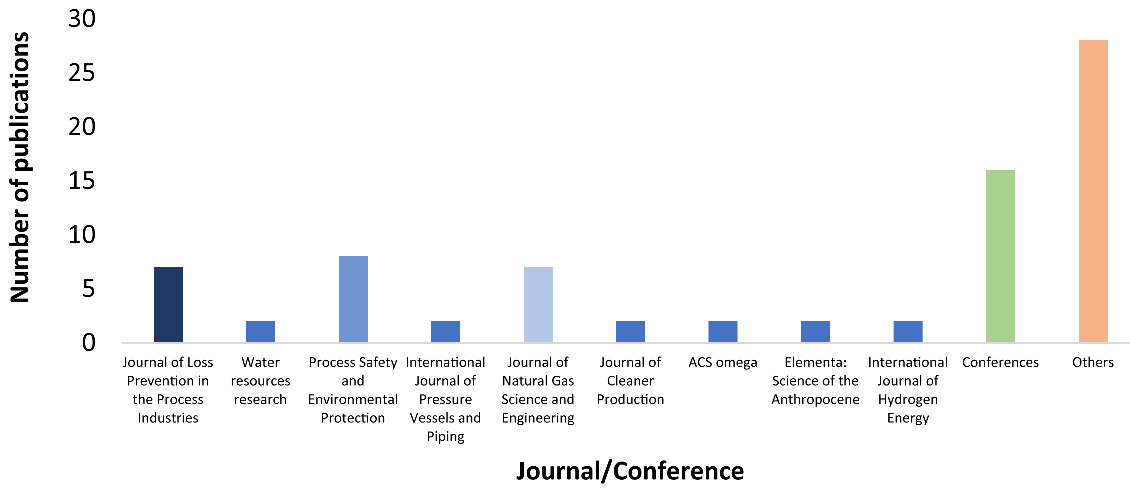

Fig. 4. Underground gas release studies distribution across the different journals and conference papers. "Others" include the journals that host only one study.

Table 2
List of primary authors engaged in at least two publications.

Author (U/R[a])	Number of publications	Total number of citations
Acton, M (U)	7	152
Link, J (R)	5	744
Lowesmith, B (U)	4	281
Deepagoda, C (U)		87
Bu, F (U)		51
Hibi, Y (U)	3	33
Silva, E.P. (U)		27
Zhou, Z (R)		79
Ramírez-Camacho, J (U)		19
Mason, E (U)		1711
Sleep, B.E. (U)		307
Ebrahimi-Moghadam, A (U)		230
Okamoto, H (U)	2	98
Cleaver, R (U)		27
Epstein, N (R)		300
Niven, R.K. (R)		306
Zhong, W (R)		144

[a] U refers to underground gas release studies, R refers to related topics' studies.

their analyses of the migration regime fundamentals. The number of citations does not come as a surprise given that literature is abundant in this domain and has started since early 19th century (Graham, 1829, 1833).

Similarly, the computational models suggested by Ebrahimi-Moghadam and the experimental (and numerical) investigations of Okamoto are highly cited (230 and 98 citations, respectively), and they both focus on underground gas releases from buried pipelines. Ebrahimi's computational model proposes expressions for the release rate out of the pipe-hole, and Okamoto's experiments imitate a release from a realistic urban buried pipeline setting. It's noteworthy to mention that some other groups have been actively investigating the related topics, such as Link (744 citations), Epstein (300 citations) and Zhong (144 citations) for the spout-fluid beds, Niven (306 citations) for fluidization, and Zhou (79 citations) for detection and localization.

To further reflect on the highly cited studies targeting underground gas releases, Table 3 provides a summary of the 15 most cited studies in this domain. The highest cited works (244 and 229 citations) were found to belong to the fundamental studies, as suggested by the previous analysis. The significant observation to make is that the top 15 cited works include studies reflecting almost each regime and/or tool highlighted, such as fundamental understanding of migration (1, 2, 6, 11), numerical modelling of migration (3, 4, 8, 10, 12, 15), and experimental analysis of migration (8, 9, 12, 15), of crater (5, 7, 13), and of all regimes (14). Hence, the listed studies in Table 3 provide a good summary of the

Table 3
Top 15 cited underground gas release studies.

Article title	Number of citations
1. Compositional simulation of groundwater contamination by organic compounds: 1. Model development and verification.	244
2. The use of Fick's law for modelling trace gas diffusion in porous media.	229
3. CFD analysis of natural gas emission from damaged pipelines: Correlation development for leakage estimation.	126
4. Correlations for estimating natural gas leakage from above-ground and buried urban distribution pipelines.	104
5. Large scale high pressure jet fires involving natural gas and natural gas/hydrogen mixtures.	101
6. Graham's laws: Simple demonstrations of gases in motion: Part I, Theory.	91
7. Large scale experiments to study fires following the rupture of high pressure pipelines conveying natural gas and natural gas/hydrogen mixtures.	90
8. Empirical research on diffusion behavior of leaked gas in the ground.	84
9. Experimental study of methane diffusion in soil for an underground gas pipe leak.	77
10. Gas leakage consequence modelling for buried gas pipelines.	63
11. Modelling transient organic vapor transport in porous media with the dusty gas model.	63
12. Effect of subsurface soil moisture variability and atmospheric conditions on methane gas migration in shallow subsurface.	59
13. The development of the PIPESAFE risk assessment package for gas transmission pipelines.	50
14. Experimental study and modelling of the consequences of small leaks on buried transmission gas pipeline.	49
15. Quantifying methane release and dispersion estimations for buried natural gas pipeline leakages.	49

major understanding established in the field of underground gas releases.

Finally, the Sankey diagram in Fig. 5 aims to quantitatively and qualitatively classify the collected studies based on the regime (migration, uplift, and crater formation) and the employed tools (fundamental, experimental, and computational). Further categorization is made based on the adopted modelling approach (mainly porous media) or focus of the study (frequently far-field investigation). Another major finding that is also included in the diagram is the "intermediate" regime implying an indefinite proper identification of the release regime by a study. Moreover, for the related domains of "Leak detection" and "Spout-fluidization", the relations are only indicative. Although numerous studies were collected, the search was not exhaustive and as such no claims can be performed, or reflections can be drawn.

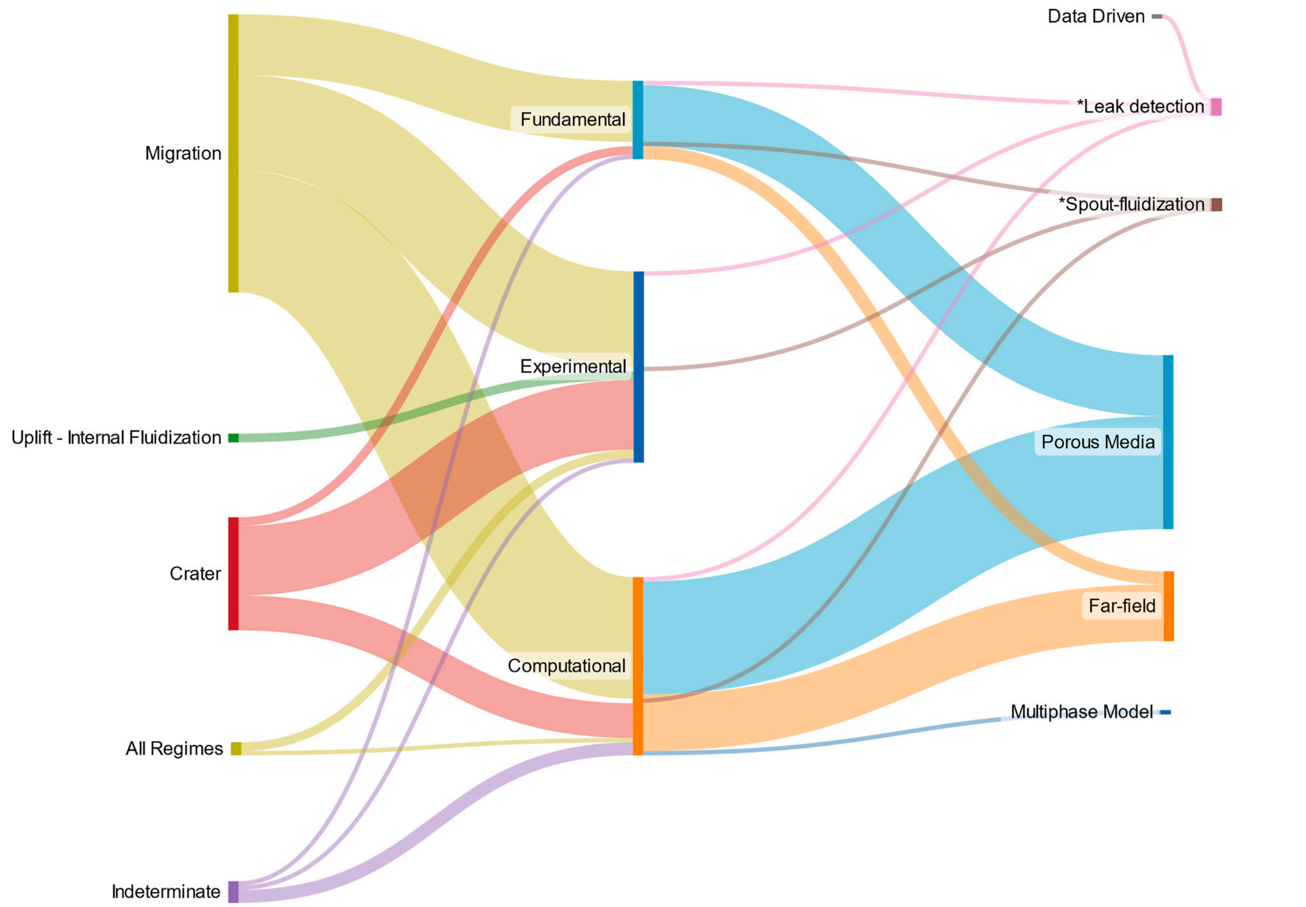

Fig. 5. Qualitative and quantitative (represented with the thickness of each line) interconnections of the reviewed works for the flow regimes (migration, uplift, and crater), main employed methods (fundamental, experimental, and computational), and other characteristic aspects.
*Leak detection and *Spout-fluidization are related topics that have been briefly discussed and thus the thickness of the connections is not indicative. The diagram was made with SankeyMATIC.

3. Main methods and topics of interest

This section reviews the collected literature based on their main contribution to the state-of-the-art and addressed challenges. Thus, it is mainly broken down according to the main objective and employed tools of the studies, e.g.: a) Fundamental studies that formulate the problem mathematically and solve it numerically; b) Differential (or computational) studies that solve the descriptions of the mathematical problem in a given set of conditions using computational tools and software; c) Experimental studies involving field scale and/or bench scale experiments and Empirical studies based on conducting/existing experimental work. The computational studies are further broken down to subsurface modelling, validation, leakage flow evaluation, influence of subsurface and surface conditions, and factors related to safety.

3.1. Fundamental (and experimental) studies on gas migration

The dominant processes during the migration of gas in soil are advection, caused by differences in pressure and specific gravity, and diffusion, caused by concentration differences (Okamoto and Gomi, 2011). The advection is mostly dominant in the vicinity of the hole while the diffusion becomes significant away from the leakage source (Gao et al., 2021). Because of this distinct behavior, it was possible to construct fundamental models dealing with one or both processes (Balseiro-Romero et al., 2018).

The viscous advective flux is usually expressed with Darcy's law, which assumes that the flow is mainly driven by the pressure difference and depends on the permeability and viscosity of the flowing material. Darcy's law is substantially used to estimate the permeability of the material by various numerical tools (Wang and Sun, 2016). Under the assumption of ideal gas, the viscous advective flux according to Darcy's law can be written in the form of:

$$N^V = -\frac{P}{RT}\frac{k}{\mu}\nabla P \tag{1}$$

The molecular diffusive flux is primarily expressed with Fick's first law, where the flux is driven by the concentration difference and is function of the diffusion coefficient. To account for the soil resistance in porous media to gas flow, this coefficient takes a specific form and is known by the effective diffusion coefficient. In a binary mixture, the diffusive flux of gas i is expressed by the following:

$$\left(N_i^D\right)_{Fick} = -D_{ij}^e C\nabla x_i \tag{2}$$

where the effective diffusion coefficient is function of the ordinary diffusion coefficient and diffusibility, which depends on the porous media geometry. One form this coefficient can take for the case of dry soils is represented by Eq. (3):

$$D_{ij}^e = Q_m D_{ij} \text{ and } Q_m = \tau n \tag{3}$$

An additional and significant phenomenon, in the gas migration through soil, is the molecule-particle collisions expressed with the Knudsen diffusion.

The simple linear addition of diffusion using Fick's law and convection using Darcy's law is referred to as the advective-diffusive model, implicitly incorporating the porous medium effects in the diffusion term and Knudsen diffusion effects in the convection term. In contrast to individually describing each flux, the Dusty Gas Model (DGM) incorporates all these processes based on the assumption that the gaseous mixture is comprised of the diffusing gases and the "dusty gas" molecules representing the particles of the porous media. Thus, the various diffusion fluxes are coupled and the equation is applicable to multi-component gas mixtures for the whole concentration range (Hibi et al., 2009) according to Eq. (4) reflecting the force-momentum balance (detailed explanation can be found in Cunningham and Williams (1980) and Mason and Malinauskas (1983)):

$$\sum_{j=1, j\neq i}^{\nu} \frac{x_i\left(N_j^D\right)_{DGM} - x_j\left(N_i^D\right)_{DGM}}{D_{ij}^e} - \frac{\left(N_i^D\right)_{DGM}}{D_i^k} = \frac{1}{RT}\nabla P_i + n' \sum_{j=1}^{\nu} x_i x_j \alpha_{ij} \nabla lnT \; i = 1, \dots, \nu \tag{4}$$

At the left-hand side, the first term represents the momentum lost due to molecule-molecule collisions between all the gas species except of the i (and of course except the particles), and the second term is the momentum lost solely by the molecule-particle collisions. At the right-hand side, the first term represents the contribution of the pressure (density) gradient on the diffusive flux and the second accounts for the contribution of the temperature gradient. The Knudsen diffusion in Eq. (4) is given by:

$$D_i^k = Q_p \left(\frac{RT}{M_i}\right)^{0.5} \tag{5}$$

where Q_p is usually a function of the pore size.

The total flux N_i^T was introduced by Mason and Evans (1969) with the simple addition of the viscous and diffusive fluxes. Using this notation, the diffusive flux expressed by the DGM (Eq. (4)) can be expressed in terms of the total flux and the viscous flux (Darcy's law, Eq. (1)). In parallel, the second term of Eq. (4) can be neglected for isothermal systems, leading to:

$$\sum_{j=1, j\neq i}^{\nu} \frac{x_i\left(N_j^T\right)_{DGM} - x_j\left(N_i^T\right)_{DGM}}{D_{ij}^e} - \frac{\left(N_i^T\right)_{DGM}}{D_i^k} = \frac{P\nabla x_i}{RT} + \left[1 + \frac{kP}{D_i^k \mu}\right] \frac{x_i \nabla P}{RT} \; i = 1, \dots, \nu \tag{6}$$

For high pressure and/or large pore diameter isothermal systems, a simplification of the DGM known as Stefan-Maxwell equation excludes the effect of the Knudsen diffusion (second term at the left-hand side), and is presented by Eq. (7):

$$\sum_{j=1, j\neq i}^{\nu} \frac{x_i\left(N_j^D\right)_{DGM} - x_j\left(N_i^D\right)_{DGM}}{D_{ij}^e} = \frac{1}{RT}\nabla P_i \; i = 1, \dots, \nu \tag{7}$$

A good number of past studies employed one or more of the above models for comparison or approximation of parameters based on experimental results, with a few studies even performing sensitivity analyses to understand the impact of the release properties on the release outcome. Characteristic examples are offered in the following paragraphs.

Sleep (1998) compared the behavior of DGM and Fick's law under the same conditions after incorporating the DGM into a simulator previously developed by Sleep and Sykes (1993). The DGM predicted significantly lower fluxes than Fick's law for lower soil permeabilities due to the increased Knudsen effect and higher fluxes for higher water saturation due to the increased pressure gradient. In addition to investigating the difference between Fick's law, Blanc's law, and the DGM, Hibi et al. (2009) extended the work of Sleep (1998) by performing one-dimensional column experiments against which they compared their simulation results, in particular the compound diffusion and compound velocity terms from the DGM. Some of the main conclusions were that the DGM can simulate any multi-component gas system, Blanc's law is only applicable for multi-component gas systems when the tracer gas is in low concentration, and Fick's law can properly describe the diffusion of a binary system for high permeabilities.

Webb and Pruess (2003) compared the DGM to the advective-diffusive model for the case of a trace gas, which led to the introduction of correction coefficients related to the tortuosity (τ_{DGM}) and Knudsen diffusion (b_{DGM}), reflecting the wall-molecule interactions. The value of τ_{DGM} was found to significantly shift away from unity for lower permeabilities and pressures (confirming the trend discussed by Sleep (1998)) whereas b_{DGM} mainly changes with the trace gas molecular weight at lower permeabilities (less than or equal to 10^{-13} m^2). The study suggested that if these coefficients are added to the advective-diffusive model, it can properly describe the binary diffusion with a trace gas.

Wakoh and Hirano (1991) estimated higher values of the diffusion coefficient than anticipated by fitting a diffusion equation to an ad-hoc experimental setup. Abu-El-Sha'r and Abriola (1997) estimated the intrinsic permeability k, the Knudsen radius Q_p (deduced from the Knudsen diffusivity), and the diffusibility Q_m by fitting the results of experiments on several kinds of sandy dry soils to the DGM (Eq. (7)). The study proposed a correlation of the Knudsen radius as function of the soil pores characteristic length (square root of the permeability) using a single gas set of experiments and another of the diffusibility as function of the porosity using binary gases set of experiments.

Similarly, Hibi and Taguchi (2011) and Hibi et al. (2012) developed experiments for two different soil permeabilities to evaluate the dispersivity, effective molecular diffusion and effective Knudsen diffusion coefficients from the DGM. Hibi et al. (2012) studied an additional term (mechanical dispersion coefficient) and suggested a correlation relating the dispersivity to the tracer gas composition. Luo et al. (2013) suggested an empirical formulation for the non-Darcy coefficient (introduced as a revision for Darcy's flow) and the pressure correction equation (introduced to account for the soil deformation and cavity formation near the hole by means of the high pressure at the inlet) using a numerical model and experiments.

The aforementioned experimental studies were performed in setups using an orifice or pipe as the gas inlet, disregarding the effect of the pipeline and hole. Okamoto and Gomi (2011) and Okamoto et al. (2014) performed full-scale experiments in a realistic network imitating a road base (Fig. 6). The advection-diffusion equation successfully simulated their experimental data while considering the impact of the gas specific gravity, pressure and concentration differences on the diffusion behavior. Parvini and Gharagouzlou (2015) developed a similar model to Okamoto et al. (2014) and used it to subsequently study the gas dispersion into either an open or closed space. The study discussed the potential resulting fires and explosions and their expected impact, indicating that there is a possibility of a flash fire only in the case of open air, whereas both fire and explosion are expected in confined spaces.

Eparu et al. (2014) suggested correlations for the transient flow rate and the diameter of the area affected by methane leakage using Darcy's law. The study revealed that lower pipeline burial depths and a horizontal position lead to the highest surface flow rates, while the lowest flows are reported for a defect under the pipeline (180°). Cheng (2014) suggested that weather (e.g., rain which affects the soil water saturation) and soil properties (sand or clay) can be crucial factors in deciding when and where to detect a leak using Fick's law with a modified diffusion coefficient to account for the viscous effects.

Although the mathematical models and experiments discussed in this paragraph describe adequately a well-established migration regime, only very few considered the effect of subsurface properties (like soil nature, water saturation), release properties (like hole direction, leak diameter, flow rate), and environmental properties (like wind speed). This theme is covered in detail in the later sections.

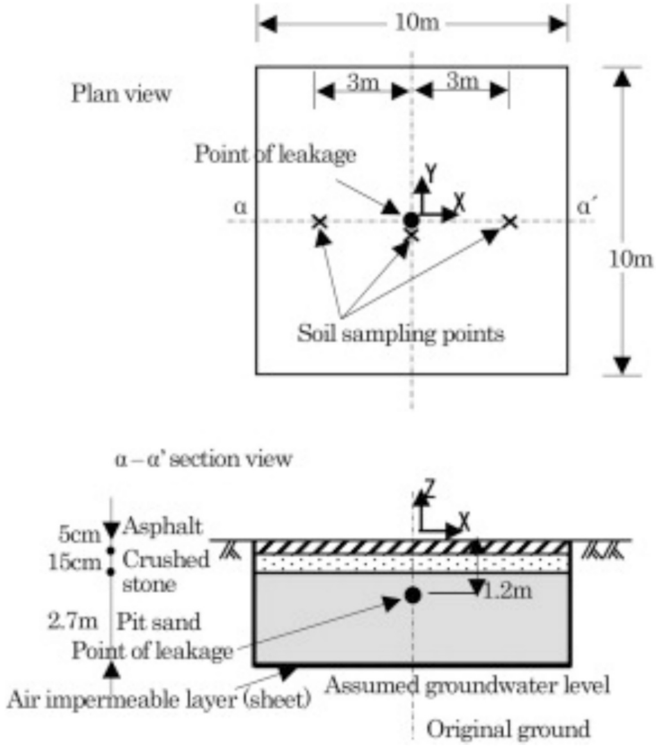

Fig. 6. Setup for the experiments conducted by Okamoto and Gomi (2011) and Okamoto et al. (2014).

3.2. Computational (and experimental) based studies on gas migration

3.2.1. Incorporating subsurface characteristics

The progression of research on the movement of gas through soil upon leakage has been significantly informed by evolving subsurface modelling approaches. Ebrahimi-Moghadam et al. (2016) and Ebrahimi-Moghadam et al. (2018) treated soil as a dry isotropic porous medium. Their 3D model (Ebrahimi-Moghadam et al., 2018) allowed the depiction of the non-uniform soil resistance in the three directions and the capture of subsonic flow at the orifice. This proved a marked advancement over their preceding 2D model (Ebrahimi-Moghadam et al., 2016) which suggested a uniform resistance and a sonic flow.

The study by Shanujah et al. (2021) added another layer of complexity by proposing a partially saturated isotropic porous medium model, introducing parametric functions for the physical and thermal properties of aggregated soils. This effectively captured their unique dual behavior resulting from the presence of two pore regions. Wang et al. (2020) took into account heat transfer and water evaporation effects, while also introducing the aspect of non-uniform soil porosity in their sensitivity analysis. They discovered that a vertical non-uniform soil structure, representative of a typical multi-layer setup in natural gas transportation pipelines, notably affected methane dispersal behavior across the soil bed, causing an underground accumulation of methane and consequentially, lower flow rates at the surface. Finally, Bezaatpour et al. (2020) offered a comprehensive model considering mass transfer, soil layering and anisotropy, variable moisture content, soil adsorption of the odorant thiol, the slope of soil layers, and the weight of the upper layers on a bottom layer (Fig. 7).

Based on the presented studies, diffusivity (governing diffusion) and permeability (dictating convection) were proven to depend on various physical and thermal properties such as porosity, tortuosity, moisture content, and thermal conductivity. Moisture content has a predominant effect as the adhesion forces between the particles and water in partially saturated soils affect the pores connectivity and air-filled space, influencing both tortuosity and porosity. As a result, the presence of water in soil pores obstructs the gas flow and limits its dispersion extent, hence, a decreased apparent diffusivity (Bezaatpour et al., 2020). While the same observation is noted in Shanujah et al. (2021), the additional correlation of the diffusivity of natural gas in moist soil with the thermal conductivity is more complex. Nonetheless, it is clear from the simulations that the gas dispersion in dry versus moist soil is driven by the gas-liquid interactions.

Moreover, heterogeneity, layer slope, upper layers' imposed weight, and moisture content can lead to asymmetrical and anisotropic gas dispersion with faster diffusion toward the gradient direction; potentially all expressed through a permeability tensor. As a result, each soil layer's distinctive properties such as texture, porosity, water content, slope, and permeability tensor were found to play a crucial role in influencing gas flow.

3.2.2. Comparison and validation

Various models for understanding gas leakage through soil have been compared and validated against each other, demonstrating a diversity of findings. Ebrahimi-Moghadam et al. (2016) and Ebrahimi-Moghadam et al. (2018) reported higher leakage rates when compared to Montiel et al. (1998) model, attributing the increase to the consideration of pipeline length after the hole. However, these models were validated only against a surface pipeline release model (Montiel et al., 1998), leading to questions about their applicability for buried pipelines.

Later, the models by Bezaatpour et al. (2020) and Bu et al. (2021a) were validated using Ebrahimi-Moghadam et al. (2018) model. A divergence in leakage flow rates was observed, largely due to Bezaatpour et al. (2020) distinct approach in modelling the soil as an anisotropic multilayered medium, in contrast to Ebrahimi-Moghadam et al. (2018) usage of an isotropic dry soil model. Meanwhile, Bu et al. (2021a) achieved a better validity, marked by a minimal average error of 3.89 %, presumably due to both studies employing dry isotropic soil models.

Models by Wang et al. (2020); Wang et al. (2021b), Bu et al. (2021b), and Zhang et al. (2021b) were validated against Yan et al. (2015) full-scale experimental work (Fig. 8), with average errors <6 %. Higher discrepancies were attributed to the computational model simplifications that hindered the exact replication of real-scale conditions. Liu et al. (2021) validated their proposed methane leakage rate correlations through lab-scale experiments, with errors of <7.2 % and 15 %. However, when these correlations were tested in full-scale experiments, errors escalated to approximately 56 %, highlighting a discrepancy possibly due to the uncaptured phenomenon of methane leaking under the pipeline. This clearly indicates the need for future modifications to these correlations.

3.2.3. Leakage flow rate evaluation

In a significant contribution to the field, Ebrahimi-Moghadam et al. (2016) and Ebrahimi-Moghadam et al. (2018) developed expressions for the volumetric flow rate of gas leakage, with respect to pipe diameter, inlet pressure, and hole diameter, for both buried and surface urban distribution pipelines. These correlations have become cornerstone in this domain and are frequently reference in literature (e.g. Bezaatpour et al., 2020; Bu et al., 2021a; Liu et al., 2021). Expanding on these foundations, Bezaatpour et al. (2020) proposed a correlation of the leakage flow rate as function of the pipeline pressure, hole diameter, and pipeline diameter, found to have a minor influence compared to the other parameters. A recent expression suggested by Bagheri and Sari (2022) was proved consistent with Bezaatpour et al. (2020)'s, and relates the release flow rate to pipeline pressure, soil porosity, hole diameter, particle size, and pipeline diameter.

Farrag and Wiley (2013) introduced the approach of relying on gas concentration measurements to deduce leakage flow rate rather than excavating, which was later adopted by both Cho et al. (2020) and Tian et al. (2022). Cho et al. (2020) evaluated underground leakage flow rate based on the subsurface transport processes occurring during an

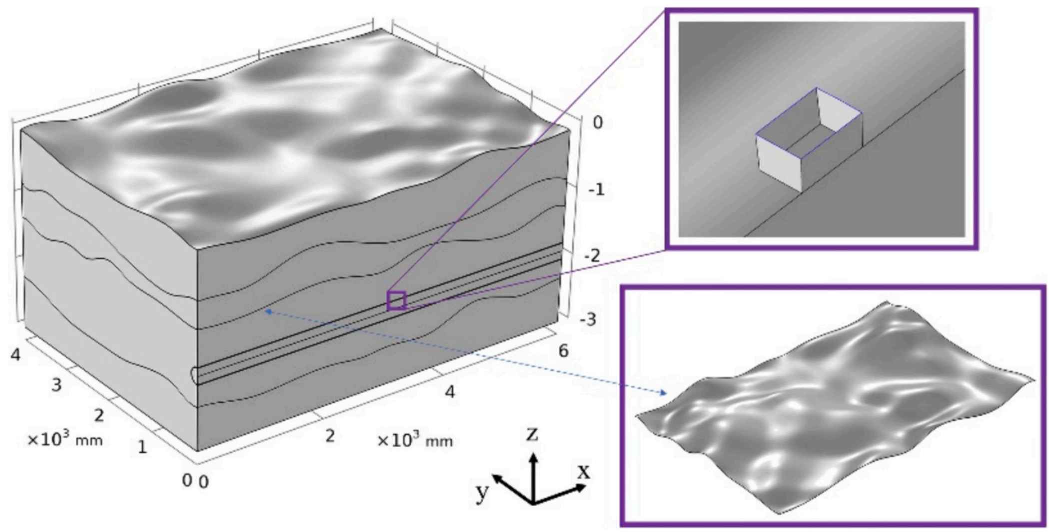

Fig. 7. The physical domain of Bezaatpour et al. (2020) considering anisotropic multilayer soil with different slopes for low pressure releases.

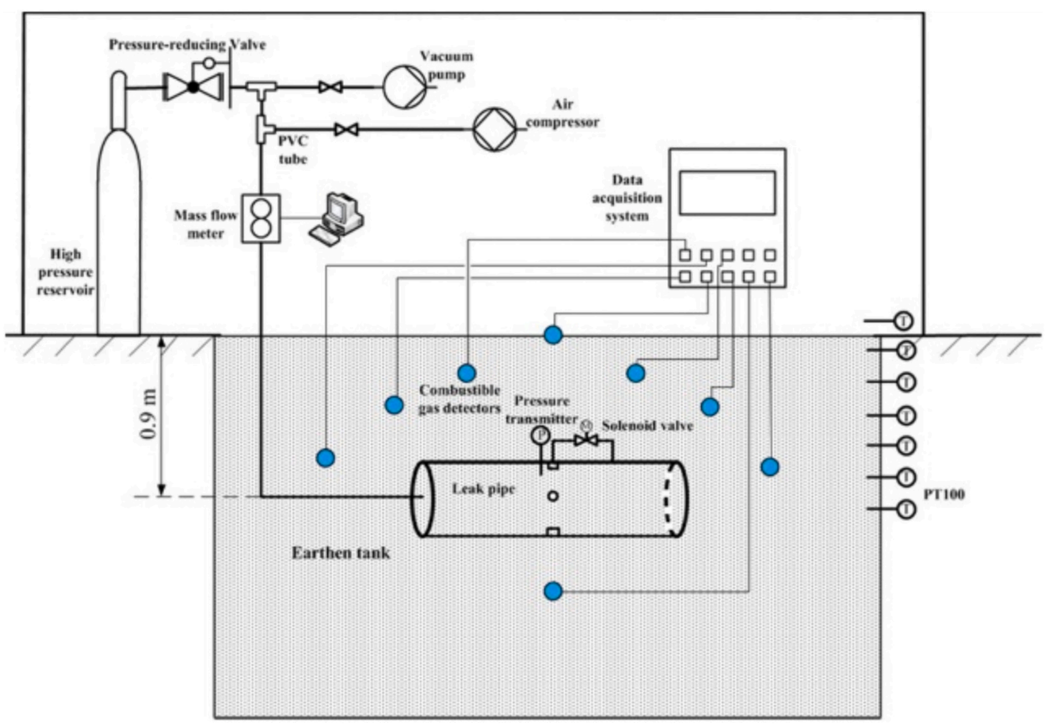

Fig. 8. Experimental setup of Yan et al. (2015).

underground natural gas release. This approach involved a dimensionless number ε linking the leakage rate to gas surface concentrations (measurable or evaluated via a software), and subsurface parameters of fluid and soil using simulated data and field scale experiments (Fig. 9). Knowing ε for a specific site, the release flow rate could be deduced from on-site surface concentration measurements during regular leak surveys. A similar novel approach was recently suggested by Tian et al. (2022) who used WindTrax model combined with experimental data to estimate the leakage flow rate using surface and aboveground gas concentrations and meteorological data.

On the other hand, Tang et al. (2009), Liu et al. (2021) and Hu et al. (2021a) devised leakage rate expressions for buried pipelines with the aid of surface pipelines expressions based on Liu et al. (2021)'s validation that the leakage rate ratio for buried to non-buried pipelines remains nearly constant. Liu et al. (2021) proposed explicit correlations of the underground leakage flow rate in terms of the leaking pressure, hole diameter, soil porosity, and particle diameter, as the burial depth, temperature, and hole shape exhibited a marginal influence on methane leakage rate and concentration. They also suggested implicit expressions derived from a gas diffusion model for temporal and spatial concentration distribution of the gas. Meanwhile, Tang et al. (2009) and Hu et al. (2021a) modified the hole model expression of the gas leakage flow rate into the atmosphere (Crowl and Louvar, 1990) by fitting their results to account for the soil layer.

A recent study by Zhu et al. (2023) proved that the error resulting from the use of the hole leakage model derived from Bernoulli's equation (surface pipelines) is 6.85 % as compared to experimental findings from an underground release of hydrogen blended natural gas at high

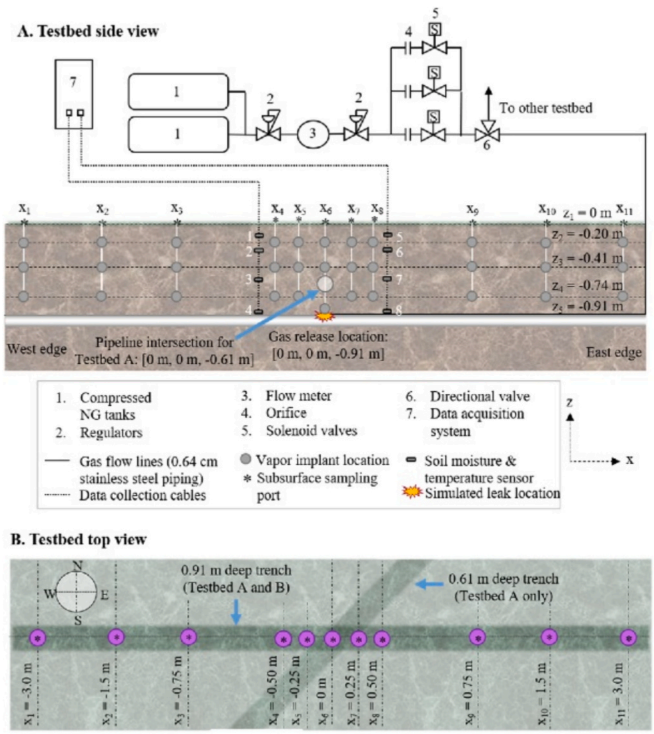

Fig. 9. Experimental setup of Cho et al. (2020): configuration A comprises the main pipeline and an adjacent stainless steel gas line and Configuration B includes only the main pipeline.

pressures (4 MPa and 5.8 MPa). This might be attributed to a free jet-like behavior exhibited at such pressures in accordance with the surface pipeline release model. This result was later adopted by Wang et al. (2023) who neglected the soil presence in their high pressures model.

3.2.4. Influence of subsurface and surface environmental conditions

Studies by Deepagoda et al. (2016), Wang et al. (2020), Gao et al. (2021) and Bu et al. (2022) have collectively demonstrated that while wind speed significantly impacts surface concentrations, it plays a less crucial role on subsurface concentrations compared to other subsurface properties. Deepagoda et al. (2016), employing a bench scale experimental setup, found that water saturation greatly influences subsurface concentrations under no-wind conditions, more so than textural configuration. Wind's influence on surface methane concentrations was found to exceed that of atmospheric temperature, aligning with Ulrich et al. (2019) conclusion that wind speed is the dominant factor affecting surface concentrations, even diluting substantial natural gas leaks (0.52 kg/h) near the ground.

Gao et al. (2021) later built upon Deepagoda et al. (2016) work by incorporating wind speed into their model and collecting full-scale experiments (Fig. 10). Both studies elucidated the intricate patterns resulting from textural configuration - where diverse textures lead to high concentration accumulations zones or low gas concentrations, depending on layer permeability and soil composition.

Gao et al. (2021) also found that the effect of different release properties is governed by the relative dominance of advection and diffusion, based on the time lapsed and distance from the leak source. Advection primarily dictates transient conditions near the source (within 1 m – 1.5 m from the hole), while diffusion controls steady state conditions further from the hole. As a result, the leak rate has a limited influence on migration extent, instead leading to a higher concentration profile and reaching steady state faster (Yan et al., 2015; Gao et al., 2021; Shanujah et al., 2021). Conversely, moisture content restricts the flow and reduces the migration extent (Bezaatpour et al., 2020; Gao et al., 2021; Shanujah et al., 2021).

Furthermore, Zeng et al. (2023) proved that hole diameter exhibit a greater effect than pipeline pressure on gas concentration in an underground tunnel space above a soil bed, indicating that natural gas in the tunnel area is more driven by concentration gradients than pressure gradients.

Lastly, Yan et al. (2015) demonstrated that the leak direction largely affects concentration above the pipeline, except for the upward direction which impacts the whole domain. Concentrations near the surface, reaching steady state faster, recorded lower values than the ones below the pipe.

3.2.5. Influence of various factors on safety parameters

Research by Deng et al. (2018) addressed the evaluation of consequence distances[1] used in designing drainage systems that redirect gases to safer areas during sudden releases. Researchers Wang et al. (2021b) and Hu et al. (2021a) introduced power functions relating alarm time with horizontal (safety) diffusion distance, defined as the distance where gas concentration reaches 5 % by volume. According to Wang et al. (2021b), the risk area[2] is mainly influenced by soil porosity and particle diameter, while hole location only affects the concentration close to the hole. Meanwhile, Zhang et al. (2021b) proved that the most significant risk areas are associated with sandy soils (followed by loamy, then clayey soils) and higher pipeline pressures, making it more likely for the soil-atmosphere interface to reach the lower explosive limit (LEL) under these conditions.

Bu et al. (2021b) proposed prediction models for first dangerous time (FDT),[3] farthest dangerous range (FDR)[4] and ground dangerous range (GDR)[5] to trace the harmful boundary for underground natural gas leakage and diffusion. Their analysis identified soil type as having the most substantial effect on these parameters, with FDT decreasing and FDR and GDR increasing from clay to loam to sand. Similarly, leakage diameter, pressure, and burial depth also had considerable effects (FDT decreases while GDR increases for higher diameters, higher pressures, and lower depths). A recent study by Su et al. (2023) validated those findings for hydrogen-enriched natural gas releases.

Furthermore, Bu et al. (2021a) examined the methane invasion distance (MID),[6] methane invasion limit state (MILS)[7] and methane invasion limit distance (MILD)[8] in different ground conditions. These properties can be instrumental in deciding the placement of natural gas pipelines (MILS and MILD) and setting monitoring points for leak detection (MID). The study found that burial depth most significantly increased MILD, while hole diameter primarily increased MID for hardened surface ground (such as asphalt roads).

Considering the displacement and deformation triggered by the leakage-induced explosion in buried pipeline, Guo et al. (2018) advocated for increasing the parallel spacing of buried pipelines and utilizing thicker pipes to lessen the impact of explosions. Zhuohua et al. (2020) emphasized that the explosive equivalent affects both the pipe and pavement, but burial predominantly affects the pavement. Therefore, it

[1] Consequence distances: diameter of the biggest cross section of the consequence region (area of 5 % concentration).

[2] Risk area: soil area where natural gas concentration is higher than 0.0283 (corresponding to LEL of 5 % vol).

[3] First dangerous time (FDT): time when methane crosses to the atmosphere domain (See *).

[4] Farthest dangerous range (FDR): longest horizontal diffusion distance attained by methane (See *).

[5] Ground dangerous range (GDR): range of methane on the ground upon achieving FDT (See *). *The reference of FDT, FDR, GDR is the LEL of methane (5 %).

[6] Methane invasion distance (MID): Furthest horizontal diffusion distance on the ground within a methane volume of 5 %.

[7] Methane invasion limit state (MILS): time at which gas attains its stable MID (see footnote 6).

[8] Methane invasion limit distance (MILD): distance achieved at MILS.

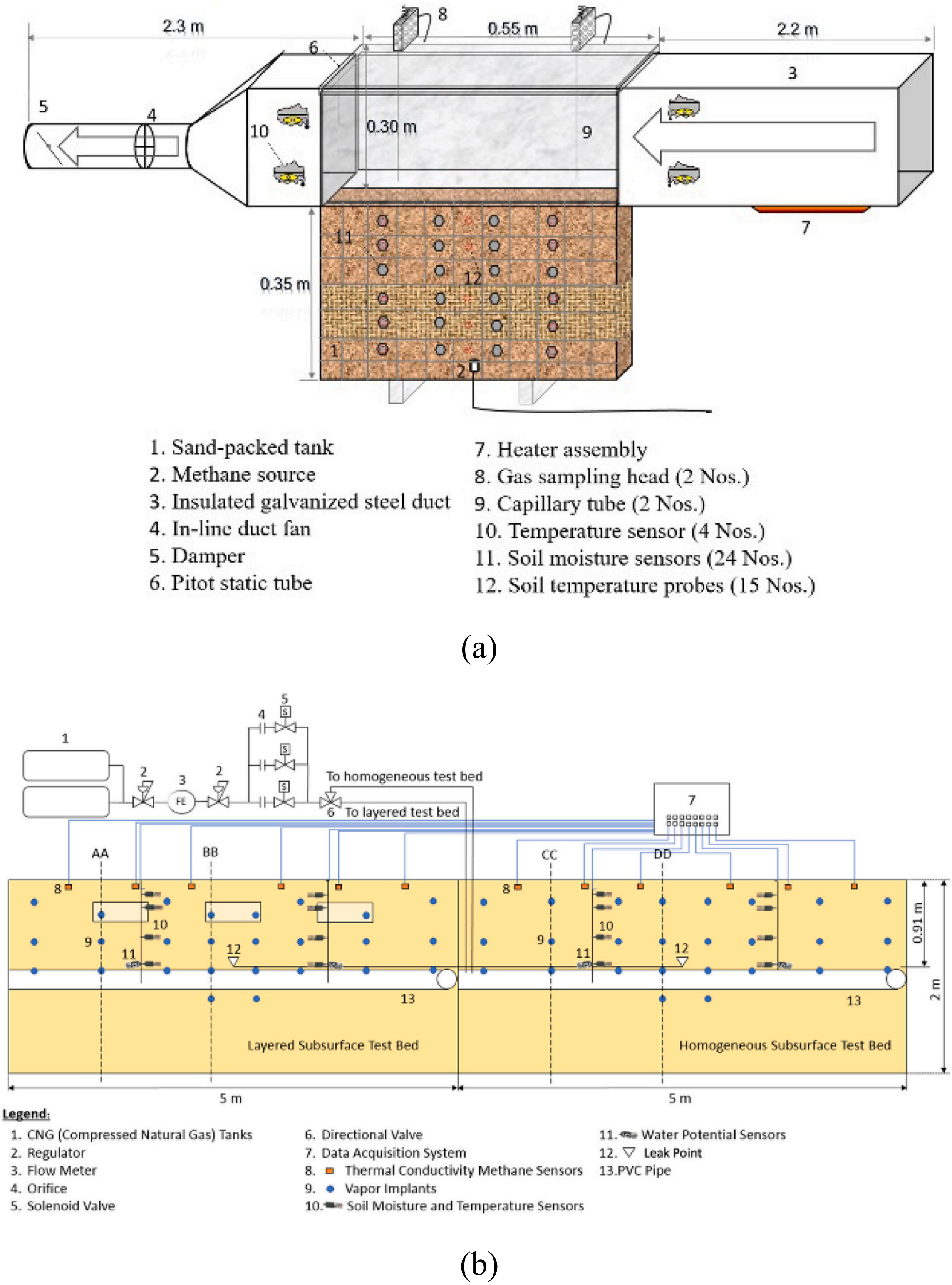

Fig. 10. Experimental setup of (a) Deepagoda et al. (2016) – bench scale and (b) Gao et al. (2021) – full-scale.

is advised to evacuate buried pipes upon leak detection and ensure that polyethylene urban gas pipelines are buried at depths >1.5 m.

3.3. Experimental and empirical studies on the crater regime

The studies on crater formation focus on characterizing the crater dimensions and analyzing the hazards associated with the release (such as fire). The first analyses date back to the 1980's, when Hoff (1983) illustrated that the rupture of buried pipelines results in a less powerful pressure wave compared to surface pipelines due to poorer gas-air mixing. However, the majority of published works are linked to the experimental works of Acton et al. group conducted by a number of international gas transmission companies, leading to a set of mathematical models incorporated in the PIPESAFE risk assessment software Acton et al. (1998).

Acton et al. (2000) discussed large scale experiments on natural gas pipelines rupture whereas Acton et al. (2010a) discussed hydrogen ruptures, which conclusions were further affirmed and linked to PHAST software by Lutostansky et al. (2013). Experiments of Acton group have demonstrated that although the mass of hydrogen released is higher than methane, the two have similar radiative properties. Moreover, variations in wind speed and crater configuration can significantly impact the observed flame and thermal radiation characteristics, and looser soils result in larger craters. Notably, the majority of the gas is released within the first couple of minutes, after which the flow and flame decay due to hydrogen's low density and rapid depressurization (Acton et al., 2010a; Lutostansky et al., 2013).

Furthermore, Acton et al. (2010b) suggested empirical formulations for assessing the recommended separation distances between underground parallel pipelines to avoid domino effect based on crater dimensions. This work led to the proposition of maximum effect distances as function of pipe diameter and soil type for pressures below 80 bar. These distances were used as estimates of the minimum safe separation distance between parallel buried pipelines (Table 4) and were documented in the UK recommendations by the Institution of Gas Engineers and Managers, IGEM/TD/1 (Institution of Gas Engineers and Managers, 2008).

Silva et al. (2016) utilized the minimum separation distance results from the Advantica model (Acton et al., 2010b) to create explicit correlations for crater width. The correlations are based on the conclusion that the maximum crater width is twice the effective distance. Silva's study also demonstrated that the pipeline diameter is the most significant parameter related to the pipeline in estimating the crater width, which is used to assess the possibility of a domino effect. Acton et al. (2018) later expanded upon Acton et al. (2010b)'s work by accounting for the failing pipeline pressure and crater profile resulting from pipeline rupture, suggesting less conservative failure probability of a pipeline following the puncture of another one using revised heat fluxes, and proposing a probabilistic approach for determining the probability of failure of a pipeline due to failure of a neighboring one.

Table 4
Effect distances suggested between underground parallel pipelines at different pipe diameters and soil types for a burial depth of approximately 1.1 m and pipeline pressure less than or equal to 80 bar. The suggested distances are measured from the center of the first pipeline to the closest point on the wall of the second pipeline (Acton et al., 2010b).

Pipeline diameter (mm)	Soil type		
	Sandy	Mixed	Clay
<323.9	7	5	3
323.9 < 457	8	5	3
457 < 610	8	5	4
610 < 762	9	6	5
762 < 914	10	6	6
914 < 1067	11	7	7
1067 < 1219	12	8	8

These assessments were among many others performed by various groups of researchers aside Acton et al. (Schram, 1991; Leis et al., 2002; Silva et al., 2016; Amaya-Gomez et al., 2018; Ramírez-Camacho et al., 2019). Despite valuable insights, these models encountered limitations in accurately representing soil, pipeline pressure, diameter, and the differentiating impact of soil types. Recent advancements, such as the probabilistic-based model suggested by Amaya-Gomez et al. (2018) and statistical analysis of past accidents performed by Ramírez-Camacho et al. (2019), have tried to address these issues, but the empirical nature of these studies limits their applications to specific experimental conditions.

The Batelle and accident-based models have been proven superior due to their consideration of crucial parameters like pipeline operating pressure, gas specific heat ratio, and soil density (Silva et al., 2016). Further refinements to these models have been made through the introduction of correction factors. Moreover, the Advantica model was developed in collaboration with several gas transmission pipeline operators and GL Noble Denton, and has since evolved to account for more parameters like failing pipeline pressure and crater profile (Acton et al., 2010b; Silva et al., 2016; Acton et al., 2018).

The original group of Acton also derived ignition probability formulations following ruptures using real incidents starting with Acton and Baldwin (2008), whose work was later updated by Acton et al. (2016). Furthermore, the group of Cleaver (Cleaver et al., 2001; Cleaver and Halford, 2015) elaborated on the mathematical models of the Acton group by modelling both the initial transient and quasi-steady stages following the rupture and ignition. They modelled the fluid flow from a predefined crater based on a single vertical jet or two jets, in addition to combustion and radiation, without accounting for the soil layer.

The different behavior of hydrogen blended natural gas on above and under-ground gas release phenomena was studied experimentally by another group, in the context of Naturalhy project (NATURALHY, 2010; Lowesmith and Hankinson, 2012; Lowesmith and Hankinson, 2013). Their findings suggest that while the lower density and faster depressurization of hydrogen result in a lower outflow of a natural gas-hydrogen mixture than natural gas alone, the flame characteristics and overpressure showed negligible difference. Additionally, the fraction of radiated heat was higher for underground pipelines, likely due to the slowed gas velocity upon interaction with crater walls. Lowesmith and Hankinson (2013)'s underground study was later used by Silva et al. (2017a, 2017b) to validate their computational models.

While substantial research has been conducted to understand jet behavior and crater formation, it remains predominantly based on empirical relations, and therefore largely limited to the conditions under which the experiments were conducted. Additionally, there has been no development of numerical models to simulate interactions with the solid bed prior to crater formation.

4. Related or supportive topics

This section summarizes three main themes that although do not directly address the objective of this review, they provide supporting and related information to one or more of the fundamental aspects discussed earlier. For example, it includes shortlisted publications (especially reviews) that describe the regimes observed in a spout-fluid and fluidization beds which are comparable and somehow equivalent to the regimes observed during underground gas releases. In the same spirit, it includes indicative publications for detection and source identification which are two recurring and critical challenges of underground releases.

4.1. Fluidization

The transitory regime between migration and crater formation has been identified as an uplift (see Section 5). This surface observation is accompanied with soil erosion (or internal fluidization) resulting from the exposure of granular beds to a localized fluid flow, and has not been extensively visited in literature.

Alsaydalani and Clayton (2014) described this phenomenon by summarizing the main literature findings on the topic. Before fluidization occurrence, low flow rates only trigger gas diffusion through the soil, which can be described by Darcy's law. At this stage, high packing densities (between 35 % and 50 %) also restrict the flow at the orifice (Massimilla et al., 1963). Higher flow rates induce more complexities, mainly as result of the fluid-matrix interactions that arise when inertial forces are no longer negligible compared to viscous forces, limiting the applicability of Darcy's law (Niven, 2002). At a specific flow, fluidization is first induced at the orifice where a fluidization zone is created near the cavity, surrounded by slowly moving or static particles (van Zyl et al., 2013). The pressure at which fluidization is initiated can be estimated using various models based on Ergun's equation (Shi et al., 1984; Peng and Fan, 1997). Further increasing the flow rates enlarges the fluidized zone into the upper layers until the whole bed is fluidized (Niven and Khalili, 1998).

Alsaydalani and Clayton (2014) continued the investigation by conducting experiments through injecting water into a Plexiglas-lined tank filled with soil. The study confirmed the previously stated findings, and showed that the flow rate and granular material properties (particle size, sphericity, permeability, bed height) affect the forces applied on the granular bed, and accordingly play a role in the determination of the onset of fluidization. Zhao et al. (2021a) performed similar experiments by injecting gas rather than water as the majority of the existing research considers water flow and the ones targeting gas leakage lack the detailed description and quantification of the gas-solid interactions. The study highlighted five principal stages for the soil erosion process leading to morphological changes such as the formation of an erosion hole, main fissure and micro fissures. Moreover, the characteristic size of the erosion hole and the number and characteristic fractal dimension of the erosion fissures presented a proportional relationship with gas pressure and an inversely proportional relationship with soil moisture content.

This study adds a substantial value toward the quantification of soil transient behavior upon gas leakage for the transitory regime of fluidization, considered a significant gap in this field. Nonetheless, more investigations should take place to improve the understanding of that regime.

4.2. Spout-fluid/spout-fluidized beds

Spouted-beds enhance the gas-particle and particle-particle contact upon mixing over traditional fluidized beds, specifically for coarse particles, making them beneficial for processes such as granulation, coating and blending. However, while the orifice diameter in fluidized beds has no limit, the orifice diameter in spouted beds does not exceed 25 average particle diameters. Combining the configuration of fluidized and spouted beds (Epstein and Grace, 2010), spout-fluid beds supply the fluid to the annulus region in addition to the central spouting region (Fig. 11a).

Therefore, spout-fluid beds offer better mixing, circulation, gas-solid contact, and particle size distribution breadth than the other two. This makes their different configurations (Fig. 11) better candidates to processes like granulation, coating, drying, pyrolysis, gasification and combustion (Shao et al., 2013).

To understand such a complex configuration, many recent studies explained the underlying phenomena behind the spout-fluid beds. Using experiments and numerical simulations based on the hard-sphere discrete particle model (DPM), Link et al. (2004) showed that spout and background fluidization velocities affect the spout penetration depth and flow patterns, respectively, and consequently the time averaged particle fluxes. Few discrepancies were noted between the experimental and simulated predictions, potentially attributed to the drag model and pseudo two-dimensional assumption. Zhong et al. (2006) found that bed height, particle property, fluidizing gas velocity, and spout nozzle width greatly influence pressure drop across the bed, maximum spouting pressure drop,[9] minimum spouting velocity[10] and minimum spout-fluidizing velocity.[11] Correlations of these parameters were suggested to assist in the design of spout-fluid beds.

Link et al. (2005), Link et al. (2008) and Nagashima et al. (2011) captured the various flow regimes in a spout-fluid bed based on pressure drop fluctuations and visual observations (Fig. 12). Link et al. (2005) and Link et al. (2008) compared their three-dimensional DPM model against the experimental findings and suggested improvement of the fluid-particle interactions for better validation. Link et al. (2007) built upon the previous DPM approach to study the particle growth behavior for a granulation process. Later, Link et al. (2009) confirmed the validity of the DPM approach followed for the fluidization and granulation processes using fiber optical measurements, by demonstrating reciprocality and qualitative agreement between numerical and experimental findings.

Ren et al. (2011) investigated the spout-fluid bed using the CFD-DEM (Discrete Element Method) to simulate the multiphase flow, a method based on the soft-sphere model in contrast to the previously mentioned studies that adopted the hard-sphere model, DPM (Link et al., 2004; Link et al., 2005; Link et al., 2007; Link et al., 2008; Link et al., 2009). Ren's work characterized the flow patterns of both gas and solid phases by considering turbulence in a cylindrical bed with a conical base, being a relevant configuration for industrial applications. Later studies by Yang et al. (2014) and Hoorijani et al. (2024) also employed the DEM approach to study the hydrodynamics in a spout-fluid bed for different flow regimes. The findings displayed a good agreement when compared to Link et al. (2008) experimental results, even better than their own simulations, presumably due to both studies adopting the soft-sphere model. In addition, a better validity was obtained with Hoorijani et al. (2024), which is probably attributed to the choice of the drag model.

The DEM followed by these studies describes the gas-solid flow efficiently for small-scale operations. Nevertheless, the computational demand becomes exhaustive for medium and large-scale operations, and other approaches like the Eulerian-Eulerian (or two-fluid model, TFM) become viable. Zhong et al. (2007) and Zhao et al. (2021b) applied the Eulerian continuum-based approach to characterize the multiphase model, and the kinetic theory of granular flow (KTGF) to describe the solid phase in a three-dimensional spout-fluid bed. Findings proved that TFM is capable of capturing the main complex flow patterns when compared to previous experimental studies, with better results validation than DPM in some cases (Zhao et al., 2021b). Recent study by Esgandari et al. (2023) suggested that proper characterization of particles and particle-particle interactions is required for TFM to achieve a good agreement with DEM and experiments.

Sutkar et al. (2013) and Shao et al. (2013) presented a comprehensive review on spout-fluid beds, incorporating the majority of the studies mentioned above. Both studies discussed the hydrodynamics of spout-fluid beds including the flow patterns, minimum spouting and spout-fluidized velocities, particle mixing and regime maps. Sutkar et al. (2013) mainly focused on summarizing the experimental and numerical studies and drawing conclusions on the hydrodynamics, whereas Shao et al. (2013) elaborated on the advances and applications of the spout-fluid beds. For further understanding of the spout-fluid beds, the reader is also referred to (Epstein and Grace, 2010; Epstein, 2020).

[9] Maximum spouting pressure drop: maximum total pressure drop required for spouting initiation.

[10] Minimum spouting velocity: minimum spouting gas velocity for spouting initiation without considering whether the annulus is fluidized or not.

[11] Minimum spout-fluidizing velocity: minimum superficial gas velocity for spouting initiation in the spout region with the annulus fluidized

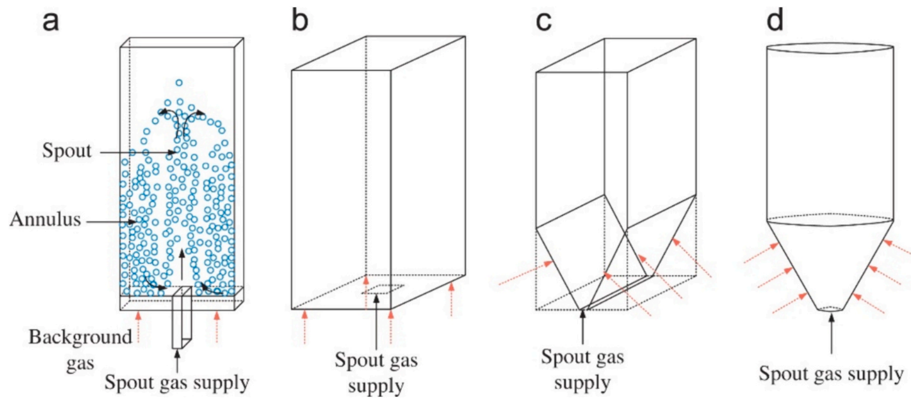

Fig. 11. The different configurations of spout-fluidized beds: (a) pseudo 2D, (b) rectangular, (c) slotted rectangular and (d) cylindrical (Sutkar et al., 2013).

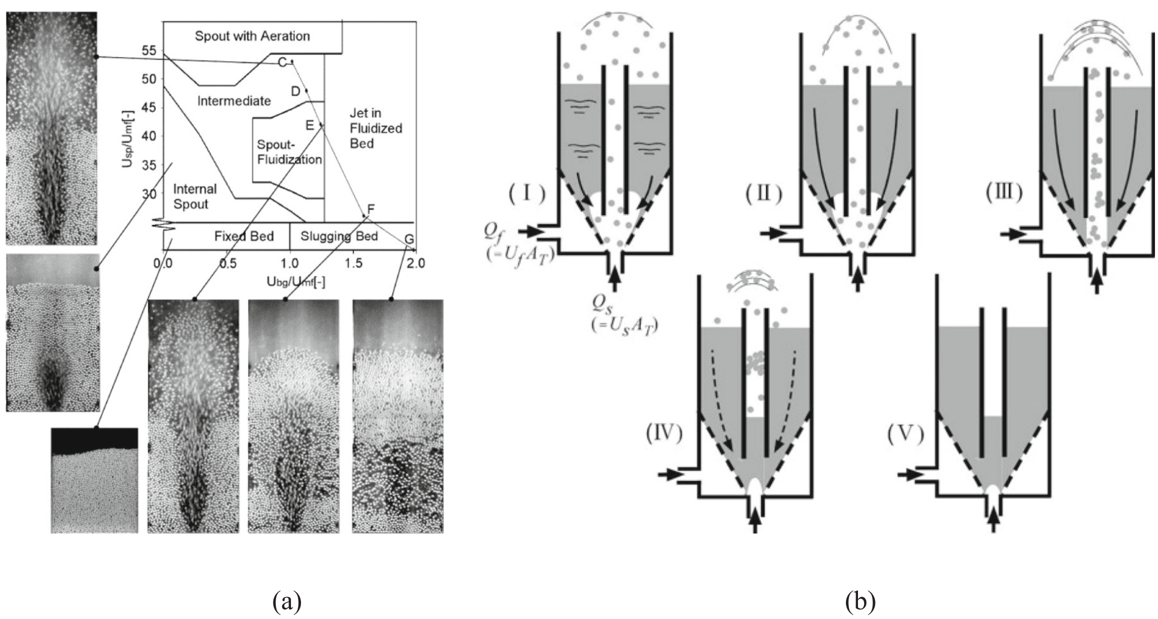

Fig. 12. Various flow regimes expected in a (a) spout-fluid bed: fixed bed, internal spout, spouting with aeration, slugging bed, spout-fluidization and jet-in-fluidized-bed regimes (Link et al., 2005; Link et al., 2008) and (b) spout-fluid bed with a draft tube: spouting with fluidization (I), spouting with aeration dispersed state (II), spouting with aeration aggressive state (III), intermittent spouting (IV), and fixed bed (V) (Nagashima et al., 2011).

4.3. Detection and localization techniques of an underground gas leak

The detection and localization of underground release sources at early stages may reduce the risk of catastrophic incidents. Few studies have emerged recently that focus on detectable levels of gas interpreted from properties such as waves, temperature, resistivity or concentration variations resulting from gas releases, rather than solely studying the fundamentals of the subsurface release process.

Li and Li (2009) proved that airborne laser equipment mounted on a helicopter can detect methane clouds dispersed from buried pipelines in specific settings with homogeneous altitudes (unlike valleys). Similar work was pursued by Botros et al. (2008) based on airborne concentration detection techniques mounted on aircrafts. Botros' findings emphasized the influence of aircraft positioning, and ground, flow, and atmospheric properties in estimating the time required before the aircraft launching for accurate detection. Based on the subsurface model, Botros et al. (2008) also highlighted the effect of subsurface and surface release parameters on the relative dominance of advection and diffusion, and subsequently on the temporal and spatial gas concentration distribution, a finding confirmed later by Gao et al. (2021) (see Section 3.2.4). Moreover, Lopezlena and Sadovnychiy (2019) suggested a transient mass and energy-based model integrated with a closed-loop boundary feedback estimator for multi-leak detection. Comparison against a real-time case study under several leak points and uncertainties in the pipeline network and instruments proved the validity of the technique for large leaks.

Kim and Lee (2009) suggested a tool to analyze acoustic wave propagation in a pipe based on acoustic signals measurements. Jiao et al. (2009) proposed a method based on the time required for sensors to receive acoustic emission (AE) signals evaluated from a waveform correlation. Ozevin and Harding (2012) proposed a novel validated approach using AE signals, by integrating the arrival time delays of the waves and the geometric connectivity for two-dimensional pipeline network configurations. Xu et al. (2016) also built upon the AE method by suggesting a multi-level approach, that consists of first estimating the region of the source, then precisely localizing it. Experimental findings confirmed a 100 % applicability of the regional estimation and a 5.3 % error of the precise localization.

Wang et al. (2021a), Zhang et al. (2021a) and Zhang et al. (2022) studied the propagation of acoustic waves along the porous medium (soil), with Wang et al. (2021a) and Zhang et al. (2021a) taking advantage of how various flow parameters (acoustic waves and sound pressure level) affect the sound in order to develop a distributed optic fiber acoustic sensing system. Further to that, Zhang et al. (2022) proposed an acoustic approach avoiding the need to install sensors prior to pipeline burial.

Earlier, Inaudi et al. (2012) employed a similar distributed fiber optic system but for temperature recordings, instead of sound, to locate small leaks from oil and multiphase systems over hundreds of meters of a buried pipeline within reasonably accurate detection distances and times. Zhou et al. (2019), Zhou et al. (2020a) and Zhou et al. (2020b) experimentally validated formulations for the temperature variation during underground gas leaks, based on the Joule-Thomson (J-T) effect, which occurs when the temperature drops as a result of the gas pressure drop. These formulations were utilized to accurately determine temperature changes, and consequently optimize the placement of fiber optic sensors and their response time.

Zhou et al. (2019) proposed that a leak can be efficiently detected when placing four optical cables at a distance of 100 mm at most in a 90° range above the pipe. Wang et al. (2021b) later recommended placing the natural gas detectors right above the pipeline instead of closer to the surface to capture the quickest growth rates and highest concentrations. Meanwhile, Zhang et al. (2020) proposed an optimization strategy to minimize the number of monitoring points based on risk evaluation. The method proved superiority when compared to existing common approaches, as the risk control rate was improved for equivalent number of monitoring locations. Bu et al. (2021a) and Bu et al. (2021b) further suggested prediction models for safety parameters that estimate the harmful extent of gas migration ((transient) MID, and FDT, FDR, GDR, respectively, see Section 3.2.5).

By comparison of different detection techniques in experimental test rigs, Xiao et al. (2021) showed that vibro-acoustic techniques offer more reliable detection and localization than accelerometers while Muggleton et al. (2020) suggested that geophones are less affected by noise than distributed acoustic sensing using optical fibers. Recent studies by Sun et al. (2021) and Tan et al. (2023) suggested methods based on resistivity profiles and machine learning algorithms, respectively. While both methods exhibited promising detection capability, the resistivity technique was significantly impacted by geological properties which limits its applicability range.

5. Toward a universal approach

A universal approach, as defined in this review, is one that encompass the entire spectrum of release regimes associated with underground gas leaks including migration, uplift, and crater formation. These regimes have been simultaneously examined by two experimental studies (Bonnaud et al., 2018; Houssin-Agbomson et al., 2018). The Joint Industrial Program (JIP) "CRATER" (2013) conducted field scale experiments to evaluate the effects of several release parameters, such as the gas type, initial pressure, hole diameter, soil nature, and release orientation on underground gas releases (Houssin-Agbomson et al., 2018). These studies revealed three primary outcomes: soil uplift (Fig. 13a), crater formation (Fig. 13b), and mixed situation. Importantly, the results suggested a negligible influence of the gas type on these outcomes, while factors such as higher pressure, sandy soil with low elasticity and cohesiveness, and an upward release orientation were found to favor crater formation.

Fig. 13. Regimes of (a) uplift and (b) crater formation as visualized by Houssin-Agbomson et al. (2018).

Continuing the investigation, GRTgaz in collaboration with INSA Rouen-Normandie performed laboratory scale tests, extending the outcomes to include migration, low and strong uplift, and crater formation (Bonnaud et al., 2018). It was noted that for sandy soil, very dry conditions (water content <5 %) precluded uplift due to lack of cohesiveness. Clayey soil, in contrast, could exhibit small crater formations due to its cohesiveness. The studies demonstrated that both clay and sand favored crater formation under conditions of higher gas pressure, larger leakage diameter, lower pipe burial depth, and lower water content. The outcome of these experimental studies was an empirical zoning graph to predict the underground gas release regime and differentiate between possible outcomes, which is a contribution toward a universal understanding of the underground gas releases.

Despite their novelty and the broad spectrum of release regimes they cover, these studies remain restricted by their specific experimental conditions and the limited data generation imposed by resource, time, and cost constraints, which might be overcome by a numerical model. Emerging from a wealth of research and investigation presented in Section 3, computational tools (and the subsequent empirical relations) have significantly progressed our understanding of underground gas leaks from buried pipelines. These studies have probed the influence of various parameters on gas release, analyzing factors from ground properties such as soil texture, configuration, porosity, and saturation, to flow properties like gas flow rate, pressure, velocity, and density, along with temperature effects and atmospheric wind. They have examined subsurface gas concentrations, surface gas concentrations, velocity profiles, pressure profiles, Mach number profiles, and streamlines, to name a few.

Nevertheless, the utility of these computational models is restricted, predominantly as the bulk of these studies engage with flow rates under the assumption of porous media (Table A1). Unfortunately, this assumption falls short when confronted with high flow rates, where gas displacement of soil becomes a substantial factor. Recognizing the potential of computational models to simulate an extensive range of conditions and observations, the door is open to extend the research by adopting more intricate multiphase models, specifically the Eulerian-Eulerian and Eulerian-Lagrangian models.

The Eulerian-Eulerian multiphase approach treats both gas and solid as a continuum. It demands the resolution of conservation mass and momentum equations for each phase, weighted by the respective volume fraction. For soil, the volume fraction of the solid phase is input to quantify particle amount, while constitutive equations, considering the granular behavior of the solid phase, help characterize the soil through the kinetic theory of granular flow. Alternatively, the Eulerian-Lagrangian approach regards gas as a continuum and the solid as a discrete phase. The accuracy of this model is superior as it tracks and characterizes each particle individually by solving Newtonian equations of motion for each using a force balance, with the gas simulation derived from the Navier-Stokes equation (Fluent, 2017). However, its superior accuracy comes at the price of higher computational costs, making it feasible for specific cases, such as dilute solid-phase flows. Conversely, the Eulerian-Eulerian approach stands as a viable alternative for an extensive array of applications, including multiphase flows (Gryczka et al., 2009; Sutkar et al., 2013; Almohammed et al., 2014).

Following the Eulerian-Eulerian representation, in an attempt to overcome the limitations imposed by experimental approaches, Srour et al. (2022) proposed a less constrained 3D model, aiming to cover the spectrum of regimes and accentuate transitions by expanding the mentioned zoning graph. However, validating such models is currently hampered by the scarcity of experimental studies and reliance on surface observations (Bonnaud et al., 2018; Houssin-Agbomson et al., 2018) or post-release excavation visualization (Bonnaud et al., 2018).

Therefore, the formulation and experimental validation of a comprehensive model, using consistent conditions and criteria, emerge as necessary steps to advance understanding in this field and succeed in the proposition of a universal approach. These criteria can potentially be the transient and spatial monitoring of release properties such as soil concentration, as this reflects the flowing behavior of the ground throughout the leak.

6. Conclusions and analysis of future research direction

Underground gas releases lead to well-known subsurface and surface phenomena which can be grouped to distinct phenomenological regimes: migration, uplift, and crater formation. These phenomena and related aspects have been studied with various methods without being exhaustive or homogenous, and the following can be concluded:

- The migration regime is primarily governed by diffusion processes. It has been extensively examined in literature, mostly in numerical studies (computational and fundamental), and to a lesser extent, but still extensively, with experimental investigations. Thus, the majority of recent studies focus on the fate and consequences of such releases and how they are affected by subsurface and atmospheric conditions.
- The crater formation regime poses, even today, theoretical and computational challenges, thus it has predominantly been explored through experimental studies and empirical formulations, e.g., to estimate the crater dimensions.
- The numerical attempts are limited both in quantity and the extent of incorporated phenomena and interactions. For example, very few studies considered the granular or impermeable subsurface features, and none, to the best of knowledge, the potential cooling/freezing effects for high pressure gas releases.
- The numerical (fundamental and computational) studies can be further categorized into far-field work (most of which are crater formation studies) and porous media studies (all of which belong to the migration regime).
  - o The far-field studies focused on consequence modelling and risk assessment (e.g., leak flow rate, explosion, fire) without simultaneously investigating the interactions of the released gas with the soil layer.
  - o Some studies modelled the phenomena following the release, assuming soil was completely ejected, while others considered simplified models of soil (e.g. solid material).
- Many of the studies explored pressure ranges that should have induced soil movement beyond mere migration, nevertheless, nothing related was reported. Hence the indeterminate regime is introduced in Fig. 5 to imply an indefinite identification of the release regime and a marginal understanding of the transitional behavior between migration and crater formation, leaving the uplift regime underexplored.
- Fluidization and spout-fluidization processes were investigated in the review considering the close relation to the underground gas release process in the context of the employed hydrodynamics. In particular, computation fluid mechanics modelling has become increasingly prevalent in elucidating the underlying physics with models, employing DPM, DEM, and TFM approaches, achieving an optimal and realistic representation of soil within feasible computational times.
- There is a limited recognition of the necessity to identify the various underground gas flow regimes simultaneously and to clearly delineate transitions across the entire spectrum; except for a couple of experimental studies and a computational study.
- The advancement in current methodologies is constrained by the idealized deterministic description of complex phenomena (e.g., diffusion, advection, fluidization) and the medium's properties (e.g., soil type, moisture content, particle shape and size, burial depth, wind speed) governing underground gas releases. Traditional models, reliant on physical process descriptions, fall short of perfectly replicating real-life scenarios.

Based on the presented gaps, the following recommendations are suggested to complement the acquired understanding in this field and contribute to a better interpretation of the release mechanisms and the subsequent consequences associated with them:

- Better understanding of the transient phenomena throughout the formation of a crater is crucial by considering the ground layer displacement after initiating the release.
- The different multiphase approaches adopted by closely related fields (such as spout-fluid processes) shall be extended to the underground gas release multiphase modelling (such as TFM, DPM, and DEM). Likely, as these approaches are adopted by the wider scientific community, they will find application to underground gas releases as a better alternative to the simplistic porous media representation predominantly used in the identified studies. A shift which could enable the simulation of regimes extending beyond migration.
- A universal comprehension of the different underground gas release regimes shall be achieved using generalized representation criteria.
  - o Further studies covering the entire spectrum of regimes with a clear delineation of the transitions are required. Primarily, experimental campaigns shall be conducted as the credibility of computational models hinges on the validation with experimental data.
  - o A universal model shall be suggested after validation by experimental findings on underground gas releases. This allows the proper identification of the release regime, hence, the proper characterization of the model depending on the soil behavior. Furthermore, this eliminates the need to label any observation as an "indeterminate" regime.
- Data-driven and physics-informed models, supported by experimental observations and supplemented with numerical simulations, offer a promising tool to mitigate these inaccuracies. Further investigations are encouraged in this domain, potentially avoiding the extensive computational resources and time required by traditional modelling and experimental setups.

Nomenclature

N^D	diffusive flux (mol/L^2 t)
N^V	viscous flux (mol/L^2 t)
N^T	total flux (mol/L^2 t)
D_{ij}^e	effective binary diffusion coefficient of gases i and j (L^2/t)
C	total molar concentration (mol/L^3)
x	mole fraction (mol/mol)
D_{ij}	binary diffusivity of gases i and j (L^2/t)
Q_m	diffusibility (dimensionless)
τ	tortuosity (dimensionless)
n	porosity (dimensionless)
R	ideal gas constant (M L^2/t^2 T mol)
T	temperature (T)
P_i	partial pressure of component i (M/L^2 t^2)
n'	gas and particles density (mol/L^3)
α_{ij}	generalized thermal diffusivity (1/L t)
D_i^k	Knudsen diffusivity (L^2/t)
Q_p	Knudsen radius (L)
M	molecular weight (M/mol)
P	pressure (M/L^2 t^2)
k	intrinsic or true permeability (L^2)
μ	viscosity (M/L t)

Acronyms

2D	two-dimensional
3D	three-dimensional
Comp.	Computational

CP	compressible
DGM	Dusty Gas Model
EOS	Equation of State
Exp.	Experimental
Fund	Fundamental
InCP	incompressible
LEL	Lower explosive limit
NA	Not applicable
PR	Peng-Robinson
SRK	Soave-Redlich-Kwong
TFM	Two-fluid model
Theor.	Theoretical
ss	steady state
tr	transient
N	No
Y	Yes

Subscripts

i, j, ν	gas component

CRediT authorship contribution statement

Ola Srour: Writing – original draft, Visualization, Validation, Investigation, Formal analysis, Conceptualization. **Konstantinos E. Kakosimos:** Writing – review & editing, Visualization, Supervision, Project administration, Investigation, Formal analysis, Conceptualization. **Luc N. Vechot:** Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Konstantinos E Kakosimos reports administrative support, equipment, drugs, or supplies, statistical analysis, travel, and writing assistance were provided by Texas A&M University at Qatar. Konstantinos E Kakosimos reports article publishing charges was provided by Qatar National Library. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

This publication was made possible by the support of the Mary Kay O'Connor Process Safety Center at Qatar. The statements made herein are solely the responsibility of the authors. Open Access funding provided by the Qatar National Library.

Appendices. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.175444.

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