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Study of the consequences of CO_2 released from high-pressure pipelines

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HIGHLIGHTS

- Incorporation of GERG-2008 EOS into CFD code for depressurisation modelling.
- Validated CFD models for CO_2 discharge and dispersion simulations.
- Comprehensive studies on source strength following full-bore rupture of CO_2 pipeline.
- Determination of consequence distances of full-bore rupture releases.
- Determination of threshold value of H_2S fraction in CO_2 mixture for risk assessment.

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ABSTRACT

The development of the Carbon Capture and Storage (CCS) technique requires an understanding of the hazards posed by the operation of high-pressure CO_2 pipelines. To allow the appropriate safety precautions to be taken, a comprehensive understanding of the consequences of unplanned CO_2 releases is essential before the deployment of CO_2 pipelines. In this paper, we present models for the predictions of discharge rate, atmospheric expansion and dispersion due to accidental CO_2 releases from high-pressure pipelines. The GERG-2008 Equation of State (EOS) was used in the discharge and expansion models. This enabled more precise 'source strength' predictions. The performance of the discharge and dispersion models was validated against experimental data. Full-bore ruptures of pipelines carrying CO_2 mixtures were simulated using the proposed discharge model. The propagation of the decompression wave in the pipeline and its influence on the release rate are discussed. The effects of major impurities in the CO_2 mixture on the discharge rate were also investigated. Considering typical CO_2 mixtures in the CCS applications, consequence distances for CO_2 pipelines of various sizes at different stagnation pressures were obtained using the dispersion model. In addition, the impact of H_2S in a CO_2 mixture was studied and the threshold value of the fraction of H_2S at the source for which the hazardous effects of H_2S become significant was obtained.

1. Introduction

In recent years, the Carbon Capture and Storage (CCS) technique has attracted considerable attention as a method of reducing what are perceived to be excessive CO_2 concentration levels in the atmosphere. In the International Energy Agency (IEA) blue map scenario, the CCS technique is expected to contribute up to 19% reduction of CO_2 emissions by 2050 (IEA, 2010). In the CCS chain, transportation of CO_2 in high-pressure pipelines from source to storage location constitutes an important link, especially when transporting large quantities of CO_2 over long distances. It is expected that extensive networks of CO_2 pipelines would be required in the near future with the growing application of CCS (Liu et al., 2014; Mazzoldi et al., 2012).

Although pipelines are generally very safe, if an accident occurs leading to release of CO_2, the consequences may be catastrophic for human and animal populations and the environment. This is because gaseous CO_2 is an asphyxiant that can lead to coma and even death at relatively high concentrations. Tolerable CO_2 concentration without negative environmental impact has been

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Nomenclature

A	area (m^2)
A_a	area at ambient pressure plane (m^2)
A_e	area at rupture exit (m^2)
C_s	roughness constant, dimensionless
f_L	dense phase fraction, dimensionless
f_V	vapour phase fraction, dimensionless
h	enthalpy (J mol^{-1})
h_a	enthalpy at ambient pressure plane (J mol^{-1})
h_e	molar enthalpy at rupture exit (J mol^{-1})
k	specific turbulent kinetic energy (m^2 s^{-2})
K	von Karman constant, dimensionless
K_s	equivalent sand-grain roughness height (m)
L	Monin-Obukhov length (m)
P	static pressure (Pa)
P_0	stagnation pressure (Pa)
P_a	ambient pressure (Pa)
P_e	pressure at rupture exit (Pa)
S	molar entropy (JK^{-1} mol^{-1})
T	static temperature (K)
T_0	stagnation temperature (K)
T_a	ambient temperature (K)
T_e	temperature at rupture exit (K)
u	velocity (m s^{-1})
u_a	velocity at ambient pressure plane (m s^{-1})
u_e	velocity at rupture exit (m s^{-1})
u_o	outflow velocity (m s^{-1})
u_r	reference wind velocity (m s^{-1})
u_*	friction velocity (m s^{-1})
w	sonic speed (m s^{-1})
w_0	sonic speed at stagnation conditions (m s^{-1})
w_m	sonic speed of gas–liquid mixture (m s^{-1})
z	height above ground (m)
z_0	surface roughness length (m)
z_r	reference height (m)
Greek letters	
α	wind shear exponent, dimensionless
ε	specific eddy dissipation rate (m^2 s^{-3})
μ	viscosity (Pa s)
ρ	density (kg m^{-3})
ρ_L	density of dense phase (kg m^{-3})
ρ_V	density of vapour phase (kg m^{-3})

identified as 2000 ppm (Mazzoldi et al., 2009). For humans, the Short Term Exposure Limit (STEL) of 15,000 ppm (1.5%) is used as a guide for maximum exposure (HSE, 2005). This is the CO_2 concentration below which no negative impact will be observed on people after a 15-min exposure. Exposure levels above 10% will lead to rapid loss of consciousness, while further exposure at higher concentrations leads to asphyxiation or worse. In order to develop controls that may be needed to protect humans, animals and the environment from possible harmful effects of pipeline failures, it is necessary to gain a better understanding of the consequence of CO_2 released from high-pressure pipelines.

Fig. 1 shows a schematic diagram of the consequence of CO_2 released from a high-pressure pipeline. In most situations, for CO_2 transportation as either cold liquid or hot supercritical vapour, a region of two-phase flow can be initiated in the pipe by the rapid depressurisation. Following the release, the two-phase fluid expands to ambient pressure as an under-expanded jet. During the expansion the jet fluid cools down significantly due to the Joule-Thompson effect (Molag and Dam, 2011). Flashing of the liquid will occur, resulting in a two-phase jet. After flashing, the CO_2 jet will contain vapour interspersed with solid particles. For a horizontal release, some of the solid CO_2 may deposit on the ground to form a dry ice bank, while the remainder may undergo sublimation in mid-flight. The dry ice bank itself will eventually undergo sublimation due to heat transfer from the environment. This may form an additional 'source' of CO_2, affecting the downstream dispersion. As a heavier-than-air gas, CO_2 tends to slump to the ground. The near-field dispersion may be dominated by the initial momentum of the jet. After travelling for a certain distance, the cloud will lose its initial momentum and be effectively mixed with air, and disperse as a 'Gaussian' cloud. To provide sufficient separation between the CO_2 pipeline and populated areas, a quantitative analysis of the risk associated with this process is essential. This requires accurate prediction of the 'source strength' (mass flow rate) and the subsequent atmospheric dispersion using appropriate mathematical models (Koornneef et al., 2010).

In attempting to fill the knowledge gaps associated with CO_2 releases, a number of experiments were carried out in the past several years. Cosham et al. (2012a) experimentally investigated the decompression behaviour of dense-phase pure CO_2 and various CO_2 mixtures, performed using a 144 m long, 168.3 mm internal diameter (ID) pipeline. Botros et al. (2013) tested the decompression of a CO_2–CH_4 mixture from a 38.1 mm ID, 42 m long shock tube. As the main concern in these two experiments was determination of the decompression wave speed, the pipeline pressure variation was only reported for very short time of release. Woolley et al. (2013) tested CO_2 releases using a 2 m^3 pressure vessel connected to a 9 m long discharge pipe of 50 mm ID. Apart from the variables inside the pipe and the vessel, the near-field temperature and concentration data was also measured to study the jet flow structure. Dalian University of Technology (DTU) has performed experiments on CO_2 releases from a 233 mm ID, 256 m long pipeline, using an orifice diameter of 50 mm at one end (Martynov et al., 2014). In order to provide data for the development of an

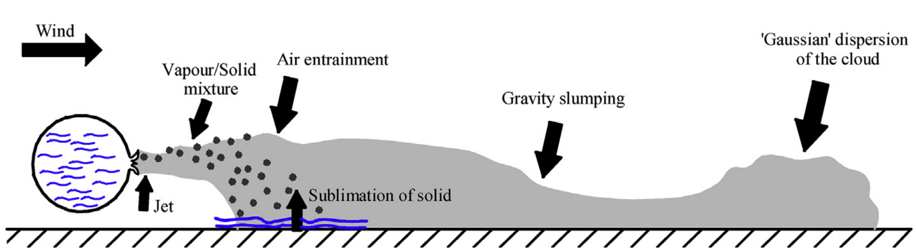

Fig. 1. CO_2 release from a high-pressure pipeline (Whitbread, 2012).