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Modelling emergency isolation of carbon dioxide pipelines

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A B S T R A C T

The development and experimental validation of a mathematical model for simulating the dynamic response of in-line Emergency Shutdown Valves (ESDVs) for high pressure Carbon Dioxide (CO_2) transportation pipelines is presented. Based on the homogeneous flow assumption, the model accounts for the pertinent valve characteristics, including the activation and closure times, as well as its proximity to the rupture location. The validation of the model is based on the comparison of its predictions against measurements taken following the controlled Full Bore Rupture (FBR) of a 113-m long, 148 mm i.d. pipeline containing CO_2 at 15.1 MPa and 300 K, incorporating a ball valve along its length. The data recorded and simulated include the transient fluid temperatures and pressures immediately upstream and downstream of the closing valve following FBR. In all cases, very good agreement between the model predictions and recorded data is reported. Importantly, the minimum fluid temperature downstream of the closing valve is found to fall below the CO_2 triple point indicating solid CO_2 formation.

1. Introduction

As part of the portfolio of technologies aimed at reducing global CO_2 emissions, Carbon Capture and Sequestration (CCS) is envisaged to make a significant contribution, with some 1.4 and 83 Gt of CO_2 expected to be captured and stored globally by 2030 and 2050, respectively (IEA, 2010). As the majority of the captured CO_2 will be transported by pipelines, the corresponding pipeline infrastructure required is expected to be enormous, according to some estimates, between 95,000 and 500,000 km in length by 2050 (Element Energy, 2010; IEA, 2010). Given that CO_2 is increasingly toxic at concentrations above 7% (vol./vol.) (Harper et al., 2011), the safety of these pipelines is of great importance and indeed pivotal to the public acceptability of CCS as a viable means for tackling the impact of global warming (Bilio et al., 2009).

A typical 100 km long, 0.8 m i.d. pipeline transporting dense-phase CO_2 at 15.1 MPa and 293 K contains ca. 45 kt of inventory. A major leak, especially near a populated area, although unlikely, must therefore be considered and appropriate mitigation steps to reduce the resulting hazard to acceptable levels must be undertaken. In the hydrocarbon industry, it is common practice to install in-line Emergency Shutdown Valves (ESDVs) to limit the amount of inventory escaping in the event of a pipeline failure. This is particularly important for the CO_2 pipeline networks envisaged.

The primary factor governing the effectiveness of an ESDV is its ability to minimise the amount of inventory escaping in the event of pipeline failure. This is governed by the valve activation time, t_a, the valve closure time, t_c, and the proximity of the valve to the rupture location.

The valve activation time, t_a, corresponds to the time elapsed between pipeline failure and valve activation, normally automatically triggered following a set drop in the normal operating pressure or through manual intervention. The valve closure time, t_c on the other hand is a design parameter governed by the rate of valve closure. t_c must be selected carefully, as too rapid a valve closure may expose the pipeline to dangerously high pressure surges which may in turn exceed the safe pipeline design pressure (Rao and Eswaran, 1993). Finally, the further the valve location is to the failure point, the greater the amount of inventory lost prior to the complete pipeline isolation will be.

Clearly, predicting the amount of inventory escaping prior to complete valve isolation following pipeline failure requires the coupling of all of the above three parameters with a relevant fluid decompression model. The simplistic assumption that the total mass of inventory released in the event of pipeline failure is equal to that held within the section of the pipeline protected by the ESDV can give rise to gross underestimations. At present, in the hydrocarbon industry, ESDVs are placed at various positions along the pipeline depending on cost, maintenance requirements and

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pipeline proximity to populated or environmentally sensitive areas. In the UK, the Health and Safety Executive recommends a minimum valve spacing of every 10–15 km for high pressure CO_2 pipelines (DNV, 2010). Surprisingly, to date, there is no publicly available study supporting this recommendation.

In a previous publication (Mahgerefteh et al., 1997), we presented the development of a computational fluid model for simulating the dynamic behaviour of inline ESDVs following accidental pipeline rupture. Initially, the outflow model was based on assuming ideal gas behaviour, using the Method of Characteristics (Wylie and Streeter, 1993) for solving the conservation equations for 1-D flow. The model was later extended to deal with real fluids including two-phase flows, by utilising the homogeneous equilibrium assumption in which the constituent fluid phases remain at thermal and mechanical equilibrium (Mahgerefteh et al., 2000). For given valve activation and closure times and proximity to the failure point, essential data such as the amount of inventory escaping and any accompanying transient pressure surges upstream of the closing valve were predicted.

Despite its success, there were two important drawbacks associated with the above valve closure dynamics model. The first was the absence of any experimental data at the time to enable its validation. The second drawback, associated with its theoretical basis, was the simplistic assumption of uniform flow velocity across the closing valve, thereby ignoring the inevitable fluid expansion-induced temperature drop. This is particularly problematic in the case of CO_2 pipelines. CO_2 exhibits exceptionally high Joule-Thomson expansion cooling. There is concern that this may lead to brittle pipeline fracture (Mahgerefteh and Atti, 2006). In addition, in the event that the CO_2 temperature falls below the fluid triple point during its expansion (−216.6 K; Perry and Green, 1997), the resulting solid CO_2 may lead to valve blockage (Huang et al., 2007).

In this paper we present an important extension of our original ESDV dynamic closure model (Mahgerefteh et al., 1997) by accounting for the change in the fluid velocity, pressure and temperature across the closing valve. This is followed by the validation of the model based on the comparison of its predictions against recent pipeline rupture experiments conducted by the UK National Grid during the course of the COOLTRANS project (Cooper and Barnett, 2014) participated by the authors.

The paper proceeds as follows. The background to the real fluid flow model employed for simulating the depressurisation and outflow within and emanating from the ruptured pipe is outlined in Section 2, this includes the details of the boundary condition developed to simulate the flow through a closing ESDV. Section 3 describes the unique ESDV experiments performed as part of the COOLTRANS project. Section 4 presents the validation of the ESDV model against the experimental data. Conclusions and recommendations for further work are drawn in Section 5.

2. Mathematical model

2.1. Pipeline flow model

The model applied in this study is based on the assumptions of one-dimensional, unsteady flow and, in the case of two-phase flow, thermodynamic and mechanical equilibrium, i.e. a single temperature, pressure and velocity. In this case the respective continuity, momentum, and energy conservation equations are given by (Zucrow and Hoffman, 1975):

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial x} = 0 \tag{1}$$

$$\rho\frac{\partial u}{\partial t} + \rho u\frac{\partial u}{\partial x} = -\frac{\partial P}{\partial x} - \rho g \sin\theta + \beta_x \tag{2}$$

$$\rho\frac{dh}{dt} - \frac{dP}{dt} = q_h - u\beta_x \tag{3}$$

where ρ, u, P, h and θ are respectively the fluid density, velocity, pressure, specific enthalpy and angle of inclination to the horizontal, which are functions of time, t, and distance, x.

The heat transfer across the pipe wall to the fluid is given by:

$$q_h = \frac{4}{D}U_h(T_{amb} - T_f) \tag{4}$$

where U_h is the overall heat transfer coefficient, D is the pipeline diameter, T_{amb} and T_f denote the ambient and the fluid temperatures respectively, and β_x, is the friction force term, which is in turn given by

$$\beta_x = -2\frac{f_w}{D}\rho u\,|u| \tag{5}$$

where f_w is the Fanning friction factor.

In the present study, the Modified Peng Robinson Equation of State (Wu and Chen, 1997) (MPR EoS) is employed as the closure equation for predicting the pertinent CO_2 properties data. Although this EoS is not capable of predicting CO_2 solid–vapour equilibrium below the triple point, it is computationally efficient and highly robust (Mahgerefteh et al., 2007). The multi-parameter GERG EoS (Kunz et al., 2007) although specifically designed for CO_2 was not employed in this study as its implementation into the flow model resulted in prohibitively long computational run times.

2.2. Valve boundary condition

The dynamic response of a ball valve acting as an ESDV is modelled in this study. In its formulation, it is assumed that the flow through the valve remains subsonic, i.e. the flow is never choked. This is reasonable given that the time during which the flow area is reduced sufficiently for choking to occur is likely to be negligible.

The instantaneous pressure drop, $\Delta P(t)$ across the closing valve is related to the volumetric flow rate, $Q(t)$ and area of flow, $A_f(t)$, via (Wylie and Streeter, 1993):

$$Q(t) = C_d(t)A_f(t)\sqrt{\frac{2\Delta P(t)}{\rho(t)}} \tag{6}$$

where $\rho(t)$ and $C_d(t)$ are the fluid density and valve discharge coefficient, respectively.

$C_d(t)$ is a function of the valve opening area given by (Wylie and Streeter, 1993):

$$C_d = A_0 + A_1\omega + A_2\omega^2 + A_3\omega^3 + A_4\omega^4 \tag{7}$$

where A_0 to A_4 are constants and ω is the percentage of the area of the valve opening. The valve area, A_f open to flow as a function of its linear closure rate, z is given by (Mahgerefteh et al., 1997):

$$A_f = 2\left[\pi R^2\frac{2\cos^{-1}\left(\frac{R-\left(\frac{2R-z}{2}\right)}{R}\right)}{360} - \left(R - \frac{(2R-z)}{2}\right)\left(\sqrt{R^2 - \left(R - \frac{(2R-z)}{2}\right)^2}\right)\right] \tag{8}$$

where R is the inner pipe radius.