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Influence of the elastic behaviour of liquids on transient flow from pressurised containments

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ABSTRACT

Release of liquids from vessels and pipelines is a very important scenario in consequence assessment. When the operating pressure is significant, its evolution and the corresponding discharge rate are affected by the elastic behaviour of the liquid. Bulk modulus is the key-driver of the related fluid-dynamics and is expected to govern the elastic-to-atmospheric pressure transition. Despite the well known physical background, the availability of release models relevant to the elastic phase is rather poor, compared to those relevant to vapours, gases and atmospheric liquids. On the other hand, if the operating pressure is high, release times and dynamics are expected to be strongly affected by the elastic behaviour and prediction of release time and flow rate is fundamental. This article carries outs a general analysis of the elastic behaviour of liquids, including water and hydrocarbons. Lumped (vessel-type) and distributed (pipeline) parameters systems have been modelled with the aim to characterize the pressure evolution during the elastic phase and to evaluate the significance of the associated duration. The findings have shown that, depending on pressure and geometric features, the importance of the elastic phase is high and that the availability of reliable and relatively simple models could be beneficial in consequence assessment. The approach is strictly valid for non-boiling liquid, but accounting for vaporisation of flashing or boiling liquids such as LPG and LNG would not imply significant complications.

1. Introduction

Non-catastrophic Loss of Containment (LOC) is the main cause of many upsets in process safety. Hazardous scenarios such as toxic clouds, fires and explosions are the final outcomes of a complex and multi-faceted phenomenon that is triggered by vapour, gaseous, liquid and two-phase releases from atmospheric and pressurised containments. The dynamics of a release in real plant scenarios depends on many geometric, process and operational factors and more and more specific models are required to adequately describe the outflow phenomena. Mainly vapour, gas and two-phase releases from vessels and piping have been treated in detail and several contributions have been provided by researchers dealing with gas-dynamics (Shapiro, 1953), (Zucrow & Hoffman, 1976), fluid-dynamics (Massey, 1983) (Chen et al., 1993), (Flatt, 1986) (Oke et al., 2003), and process safety (CCPS, 2000) (TNO, 2005), due to the complexity of compressible fluids and to the numerous implications at and downstream of the discharge outlet. Conversely, non-boiling liquids discharge has received less attention essentially because of its relatively simple and univocal behaviour. Generally speaking, liquid flow rate from a vessel is calculated according to Torricelli's formula, which is obtained just applying Bernoulli's law (Fauske and Epstein, 1988). This formula is adopted considering the liquid static head eventually along with an additional constant pressure at the top of the tank, for example if the vessel is padded with an inert gas (Crowl and Louvar, 2014). Liquefied gases and boiling liquids are associated with a slow or violent depressurisation depending on geometry and on liquid properties, which may result in an irregular pressure behaviour in the vessel headspace (Wilday, 1992). However, should a pressurised non-boiling liquid be affected by a sudden pressure drop due to the discharge through a hole in the containment wall, liquid elasticity is expected to play a significant role until the system reaches pure Torricelli's regime at atmospheric pressure. For equipment with aspect ratio greater than 1, such as pipelines or elongated vessels, TNO (2005) states that a decompression wave will be travelling into the system and reports that very few literature data are available. This article focuses on the influence of liquid elasticity on the atmospheric depressurisation of vessels and elongated structures following a release through a hole.

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2. Objectives and methodology

The present article aims to the following objectives:

- to investigate the elastic behaviour of liquids subject to medium and high pressure
- to screen the dependency of the bulk modulus on main process variables, such as temperature and pressure
- to evaluate the influence of this parameter on the duration and the dynamics of the release during the elastic phase
- to model non - boiling liquid release from pressurised containments

The analysis has been carried out with reference to two main groups of systems which are expected to behave differently in regards to the elastic properties of liquids. Specifically, lumped parameters and (high aspect ratio) distributed parameters have been analysed, and the resulting behaviour has been assessed and compared. The findings have proved that, if pressure is high, the elastic phase duration is significant and that the relevant configuration has to be described by calculation equations which are totally different from those generally available in the reference literature. The examined release scenario is likely to take place both during normal operation, commissioning and start-up and only deals with non-boiling liquids.

3. Bulk modulus

3.1. Definition

Fluid elasticity is described, according to Hooke's law, through the ratio:

$$B_n = \frac{stress}{volumetric\_strain} \tag{1}$$

where B is the bulk modulus and n identifies a generic process. If v is the specific volume and P is the pressure:

$$B_n = -v \cdot \left(\frac{\partial P}{\partial v}\right)_n \tag{2}$$

Many processes are thermodynamically possible, but only the isothermal bulk modulus and the adiabatic bulk modulus are practically used:

$$B_T = -v \cdot \left(\frac{\partial P}{\partial v}\right)_T \tag{3}$$

$$B_K = -v \cdot \left(\frac{\partial P}{\partial v}\right)_K \tag{4}$$

B_T and B_K of a liquid of given API gravity and at pressure P (psig) and temperature T (°R) can be calculated through empirical ARCO formulas as given by Shashi Menon (2004):

$$B_T = a_T + b_T \cdot P - c_T \cdot T^{1/2} + d_T \cdot T^{3/2} - e_K \cdot API^{3/2} \tag{5}$$

$$B_K = a_K + b_K \cdot P - c_K \cdot T^{1/2} - d_K \cdot API - e_K \cdot API^2 + f_K \cdot T \cdot API \tag{6}$$

where:

- a, b, c, d, e, f are constants
- P is the pressure, psig
- T is the temperature, °R

Table 1 shows the value of constants (Shashi Menon, 2004) and Table 2 includes B_T and B_K values for some process liquids at 20 °C and 1 atm.

Table 1
ARCO equation constants for bulk moduli calculation (Shashi Menon, 2004).

Isothermal	Value	Adiabatic	Value
a_T	2.619×10^6	a_K	1.286×10^6
b_T	9.203	b_K	13.55
c_T	1.417×10^5	c_K	4.122×10^4
d_T	73.05	d_K	4.53×10^3
e_T	341	e_K	10.59
–	–	f_K	3.228

ARCO equations have no specific theoretical basis, but are very useful for a general identification of the variables affecting bulk moduli value. Their correctness can be proved according to Bair (2014), which, on the basis of Murnaghan EoS, has proposed the following equation for the isothermal bulk modulus of some diesel fuels:

$$B_T = K_o + K_o' \cdot P \tag{7}$$

$$K_o = K_{oo} \cdot \exp(-\beta_k \cdot T)) \tag{8}$$

Values of β_K, K_o' and K_{oo} for four investigated diesel fuels have been included in Table 3 (Bair, 2014). Finally, bulk moduli relevant to water (Totten and De Negri, 2011), propane (Younglove and Ely, 1987) and benzene (Forsythe, 2003) at different pressures have been included in Table 4.

3.1.1. Bulk modulus and sound velocity

Sound velocity can be expressed in terms of the bulk modulus according to the Newton–Laplace equation:

$$u = \sqrt{\frac{B}{\rho}} \tag{9}$$

Due to the sound velocity definition:

$$u = \sqrt{\left(\frac{\partial P}{\partial \rho}\right)_S} \tag{10}$$

we recognise that B in equation (9) is the adiabatic bulk modulus.

4. Setting up the release scenario

4.1. Geometry

Given the nature of pressure transition, two main configurations have been assumed as representative of the possible scenarios:

- a vessel-type component, which is defined as a containment whose aspect ratio is around 1.0
- a pipeline-type component, which is a defined as a component whose length L is much greater the transversal size (diameter)

These two items are expected to show a completely different behaviour when a pressure drop occurs through a hole. Specifically, the vessel-type item can be assumed as a lumped parameters system, so time will be the only one independent variable. The pipeline-type item has been assumed as a distributed parameters system, because a compression pressure wave is expected to move from the hole zone, so time and longitudinal coordinate x are assumed as independent variables. The two configurations have been show in Fig. 1.