Annals of Nuclear Energy 111 (2018) 1–11

Contents lists available at ScienceDirect

Annals of Nuclear Energy

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

A non-equilibrium relaxation model for fast depressurization of pipelines

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ARTICLE INFO

Article history:
Received 24 December 2016
Received in revised form 5 May 2017
Accepted 16 August 2017
Available online 4 September 2017

Keywords:
Non-equilibrium
Depressurization
Liquid–vapor
Blowdown
Numerical method

ABSTRACT

In this paper, transient depressurization of high pressure pipelines containing initially subcooled liquid is simulated numerically by using thermodynamic non-equilibrium and choking condition model. The numerical method relies on finite volume. The convective terms of cell boundaries are discretized by Advection Upstream Splitting Method (AUSM+ - up) with a proposal of partially implicit approach for source terms. Different void fraction correlations are applied to simulate two phase shock tubes as well as the depressurization process. By comparison between the present results and previous experimental data, the best void fraction correlation is introduced. The results indicate that the propagation of a strong evaporation wave toward the closed end drops the inside pressure of the pipe to a value below the initial saturation pressure. As the wave is reflected from the closed end, a slight pressure undershoot is developed. At the late stage of the depressurization, the pressure along the pipe reduces at a moderate rate. Maximum heat transfer rate and minimum pipe wall temperature occur at the open end.

1. Introduction

Safety analysis of the industrial installations such as Light Water Reactor (LWR) requires the consideration of the fast depressurization of pressure vessels or high pressure pipelines containing initially subcooled or saturated liquids. Such processes may occur as a result of a structural failure or an operational opening of safety valves. In order to mitigate the damaging effects of such a failure, it is essential to predict accurately the transient parameters of the pipeline failure, including the leakage flow rate, pressure and void fraction. However, full scale experiments are not always feasible; therefore the numerical simulation of such processes is desirable.

The numerical simulation of compressed liquid requires the consideration of several complex processes, making it challenging. Experimental investigations indicated that during the depressurization of a pipeline containing initially pressurized liquid, liquid–vapor two-phase flow had occurred in the pipe (Han et al., 2013; Witlox et al., 2014). Immediately after the onset of depressurization, a rarefaction wave propagates through the intact end and is followed by flashing front propagation. Moreover, the flow at the open end can be choked which results in the reduced rate of depressurization rate. Therefore, careful consideration of heat and mass transfer, frictional losses and implementing proper boundary conditions in the numerical simulation is indispensable for the successful simulation of these processes.

The majority of existing works about the numerical simulation of compressed liquid pipeline depressurization has employed homogeneous equilibrium model (HEM) that is based on the mechanical and thermodynamic equilibrium assumption, namely the local equality of pressure, velocity and temperature between the phases (Fairuzov, 2000; 1998a, 1998b; Mahgerefteh et al., 2006; Moloudi and Esfahani, 2014; Popescu, 2009). Recent experimental observations of full bore rupture of pressurized pipelines indicate that flow pattern is fully dispersed flow (Brown et al., 2013). Therefore neglecting velocity slip between the phases could be a reasonable assumption. However, previous studies indicate that thermal non-equilibrium could have a determining role in the correct simulation of full bore rupture problems (Fairuzov, 2000, 1998a, 1998b).

Xu et al. (2014) modeled pipeline depressurization by employing arbitrary Lagrangian-Eulerian method (ALE) to solve the system of the equations of homogeneous equilibrium model. They validated their model against fast decompression of a rich gas pipeline and slow blowdown cases of a liquefied petroleum gas pipeline. The predicted pressure and temperature are found to be in good agreement with the measurements; however total fluid inventory is over-predicted by approximately 20% during the release period. Since HEM neglects thermal non-equilibrium

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http://dx.doi.org/10.1016/j.anucene.2017.08.025
0306-4549/

between the phases the simulation overestimates the vapor generation rate.

Recently, Brown et al. (2014) accounted for the thermal and mechanical non-equilibrium effects during depressurization of a CO_2 pipeline by utilizing two-fluid model with simple constitutive relations describing inter-phase mass, heat and momentum transfer. They concluded that predictions were in reasonably good agreement with the experimental data; however the results were strongly dependent on the thermal relaxation time. Further investigation of the simulation of transient flow in pipes revealed that two-fluid model does not provide substantially better predictions than the homogeneous equilibrium model, unless specially adapted models for friction and heat transfer are provided for the two-fluid model (Munkejord and Hammer, 2015). Nevertheless, the development of such models would require detailed local experimental data.

Bartosiewicz and Seynhaeve (2014) employed the model of Delayed Equilibrium Model (DEM) to account for the thermal non-equilibrium between the phases. However, their study was limited to the choked or critical flow in steady state or quasi-steady state conditions. Brown et al. (2013) simulated discharge behavior following the full bore rupture of dense phase CO_2 pipelines by using the homogeneous relaxation model and found that neglecting delayed phase transition results in underestimating the discharge rate. The homogeneous relaxation model is presented by Downar-Zapolski et al. (1996) and is employed by several authors to numerically simulate steady flashing flows (Gopalakrishnan and Schmidt, 2008; Neroorkar et al., 2012; Saha et al., 2016). Barret et al. (2002) used this model to compute unsteady flashing flows in variable cross section ducts. Original non-equilibrium relaxation model employs a simple correlation for the void fraction which can lead to erroneous results.

In this study, the transient problem of the pipeline depressurization containing initially subcooled liquid is numerically solved to study the model of relaxation time affected by vapor void fraction. Model equations are discretized by finite volume method including AUSM+ - up scheme (Liou, 2006) for fluxes calculation at cell boundaries. Proper implementation of choking conditions is presented and a partially implicit method is proposed to deal with source terms. This method has advantage over the fractional splitting method since it requires the variables to be calculated once at each time step. The performance and stability of the numerical scheme is also investigated by simulating shock tubes at low Mach numbers.

2. Governing equations

In this paper, the relaxation model of Downar-Zapolski et al. (1996) is employed to account for the thermal non-equilibrium between two phases in a pipe. This model was previously used by Brown et al. (2013) to simulate discharge behavior following the full bore rupture of dense phase CO_2 pipelines. The two-phase flow is assumed to be one-dimensional with friction and heat transfer from the wall. The pipe is assumed to be made of one percent carbon steel and the ratio of wall thickness to the internal diameter is 0.07. At the initial state, fluid pressure and temperature are assumed to be uniform and the pipe wall is in thermal equilibrium with the fluid.

Relaxation model consists of three conservation laws of mass, momentum, energy for the two-phase mixture in addition to the mass balance law for the vapor phase.

$$\frac{\partial \mathbf{U}}{\partial t}+\frac{\partial \mathbf{F}}{\partial z}=\mathbf{S} \tag{1}$$

where,

$$\mathbf{U}=\begin{bmatrix}\rho\\ \rho u\\ E\\ \rho x\end{bmatrix},\quad \mathbf{F}=\begin{bmatrix}\rho u\\ \rho u^2+p\\ u(E+p)\\ \rho u x\end{bmatrix},\quad \mathbf{S}=\begin{bmatrix}0\\ -2f\rho u^2/D_i\\ 4h_{TP}(T_w|_{r=D_i/2}-T_{ml})/D_i\\ -\rho(x-\bar{x})/\theta\end{bmatrix} \tag{2}$$

where, $\mathbf{U}$ is the vector of conservative variables and $\mathbf{F}$ is the vector function of $\mathbf{U}$ ρ, p, u, x, $\bar{x}$, θ, f and h_{Tp} represent respectively mixture density, pressure, velocity, non-equilibrium vapor quality, equilibrium vapor quality, the relaxation time, Fanning friction factor and heat transfer coefficient. D_i is the pipe inner diameter and $E=\rho e+0.5\rho u^2$. T_{ml} is the temperature of the metastable liquid.

The transient two-dimensional heat equation through the pipe wall is as follows.

$$(\rho c_p)_w\frac{\partial T_w}{\partial t}=\frac{k_w}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T_w}{\partial r}\right)+k_w\frac{\partial^2 T_w}{\partial z^2} \tag{3}$$

under the following boundary and initial conditions.

$$\begin{aligned} k_w\tfrac{\partial T_w}{\partial r}|_{r=D_o/2}&=h_\infty(T_\infty-T_w|_{r=D_o/2})\\ k_w\tfrac{\partial T_w}{\partial r}|_{r=D_i/2}&=h_{TP}(T_w|_{r=D_i/2}-T_{ml})\\ \tfrac{\partial T_w}{\partial z}|_{z=0}&=\tfrac{\partial T_w}{\partial z}|_{z=L}=0\\ T_w(r,z,0)|_{z=L}&=T_\infty \end{aligned} \tag{4a-d}$$

To close the system of governing equations (Eqs. (1)-(3)), for eleven unknown variables of ρ, p, u, E, x, $\bar{x}$, θ, f, h_{Tp}, h_∞ and T_w, six constitutive equations are required. These equations include an equation of state, equilibrium vapor quality, relaxation time as well as the relation for void fraction, friction factor, single and two-phase heat transfer coefficients for outside and inside of the pipe. Details of which are presented in the following sections.

2.1. Constitutive equations

2.1.1. Equation of state

A proper equation of state is necessary to determine the phase equilibrium and the thermodynamic properties of subcooled liquid, metastable liquid and saturated vapor. In this regard the equation of state given by International Association for the Properties of Water and Steam (Wagner and Pruß, 2002) is employed. To speed up calculations, the backward correlations given in the industrial version (Cooper and Dooley, 2012) and also the highly efficient method presented by Mao et al. (2011) are used to calculate the saturated properties of water.

2.1.2. Vapor quality

Assuming that the vapor is saturated and the liquid is metastable, the specific internal energy and density of the two-phase mixture are defined as:

$$e=xe_g+(1-x)e_{ml} \tag{5}$$

$$\frac{1}{\rho}=\frac{x}{\rho_g}+\frac{1-x}{\rho_{ml}} \tag{6}$$

and based on the thermodynamic equilibrium, the vapor quality is $\bar{x}=(h-h_f)/h_{fg}$.where, h stands the specific enthalpy of the two-phase mixture and subscripts "g", "f" and "ml" respectively refer to the saturated vapor, saturated liquid and the metastable liquid.

2.1.3. Speed of sound

The mixture speed of sound and can be calculated from:

$$a=\frac{1}{\rho}\left[\frac{p+\left(\frac{\partial e_{ml}}{\partial v_{ml}}\right)_p}{x\frac{de_g}{dp}+(1-x)\left(\frac{\partial e_{ml}}{\partial p}\right)_{v_{ml}}-x\frac{dv_g}{dp}\left(\frac{\partial e_{ml}}{\partial v_{ml}}\right)_p}\right]^{0.5} \tag{7}$$