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Mathematical modelling on rapid decompression in base natural gas mixtures under rupturing

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ABSTRACT

The paper presents a one-dimensional mathematical model of transient compressible thermal multi-component gas mixture flows in pipes. The set of the mass, momentum and enthalpy conservation equations is solved for gas phase in the model. Thermo-physical properties of multi-component gas mixture are calculated by solving the Equation of State (EOS) model. The Soave–Redlich–Kwong (SRK–EOS) model is chosen. Gas mixture viscosity is calculated on the basis of the Lee–Gonzales–Eakin (LGE) correlation. Numerical analysis on rapid decompression process in a shock tube having base natural gases is performed by using the proposed mathematical model. The model is successfully validated on the experimental measurements of the decompression wave speed in base natural gas mixtures. The proposed mathematical model shows a very good agreement with the experiments in a wide range of pressure values and predicts the decompression in base natural gases much better than analytical and mathematical models, which are available from the open source literature.

Keywords: Mathematical; Modelling; Rapid; Gas mixture; Decompression

1. Introduction

A rupture on the pipeline wall due to fracture brings numerous problems for oil and gas engineers. It takes a lot of efforts fixing the problem. The fracture on the pipe wall does not propagate far and is arrested quickly, if a pipeline has been designed by employing of new advances in fracture propagation control. The fracture propagation control in natural gas pipeline transport service is usually made by using the Battelle two-curve method, which was developed by the Battelle Columbus Laboratories in order to determine the fracture arrest toughness (Eiber et al., 1993, 2004). The fracture propagation speed in the pipeline wall and the decompression wave speed in gas mixtures are used together in the Battelle analysis. The fracture propagation is arrested, if the decompression wave speed in gas mixture is quicker than the fracture propagation velocity in the pipeline wall material. Therefore, the information about the decompression wave speed in different gas mixtures is very important for the fracture propagation control and for the pipeline design.

The fluid mixture composition, pipeline inner diameter, pressure, and temperature significantly influence on the decompression wave speed. The decompression in natural gas mixtures is very rapid non-isothermal process. A transient mathematical model of compressible thermal multi-component gas mixture flow in pipes gives very detailed information on basic flow parameter's distribution and flow behaviour in a wide range of operating parameters. Information about the mathematical modelling on rapid decompression process in natural gas mixtures is extremely limited in the open source literature. Most part of papers contains very simplified engineering analysis. Experimental measurements of the decompression wave speed in dry, base and rich natural gas mixtures were conducted by TransCanada PipeLines (TCPL) (Botros et al., 2003, 2004, 2007, 2010a,b). Measurements were performed much more intensively compared to mathematical modelling. The influence of a shock tube inner diameter, gas mixture composition, pressure, and temperature was examined in details experimentally. Pressure values in those studies were varied in the range between 10 MPa and 37 MPa (Botros et al., 2003, 2010a,b). Most of measurements were made on small-diameter shock tubes, where the friction force influences on the flow behaviour much stronger compared to large-diameter pipes.

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Nomenclature

D_{pipe}	diameter of the pipe (m)
D_1, D_2, D_3	parameters of the viscosity correlation
$D_{P1}, D_{P8}, D_{P5}, D_{P6}$	distances between PT locations and the rupture end of the pipe (m)
h_G	enthalpy of the fluid (J/kg)
M	molar mass of the gas mixture (g/mol)
MW_g	molecular weight of the gas mixture (g/mol)
N	number of components in the gas mixture
P	total pressure (MPa)
P_{Ci}	critical pressure value of the component i of gas mixture (MPa)
$P_{initial}$	initial pressure in the shock tube before rupturing (MPa)
R	universal gas constant (J/mol/K)
R_{G-Wall}	gas mixture to wall friction term
S	cross-sectional area of the pipe (m^2)
t	time (s)
T	temperature of the gas mixture (K)
T_{Ci}	critical temperature value of the component i of gas mixture (K)
$T_{initial}$	initial temperature in the shock tube before rupturing (K)
U_G	velocity of the gas mixture (m/s)
V	volume of the gas mixture (m^3)
z	axial co-ordinate of the decompression tube (m)
z_i	mole fraction of the component i of gas mixture
Z	compressibility factor of the gas mixture
s	volume fraction of the gas mixture
ε	internal surface roughness (m)
μ_G	gas mixture viscosity (Pa s)
ξ_{G-Wall}	gas to wall friction coefficient
Π	perimeter of the pipe (m)
ρ_G	density of the gas mixture (kg/m^3)
τ_{G-Wall}	gas mixture to wall friction term
ω_i	acentric factor of the component i of gas mixture

The program called GASDECOM (Eiber et al., 1993) is the most well-known software in the field of natural gas transport engineering. It calculates the decompression wave speed values in natural gases (Botros et al., 2003, 2007) by using analytical correlations for gas mixture hydrodynamics together with different EOS models. The friction force is not taken into account in GASDECOM's model. Thus, the application area is limited on large-diameter pipelines, where accurate calculation of thermo-physical fluid properties is much more important compared to proper modelling of fluid hydrodynamic behaviour. The program predicts the decompression wave speed values with a reasonably good level of accuracy compared to the experimental data if those experimental values are determined from pressure transducers, which are mounted in the rupture end area of the tube, where the friction's influence is not very strong. The comparison between measured data and GASDECOM calculations is poor, if the decompression wave speed is determined experimentally from pressure transducers, which are located far away from the rupture end of the pipe, and where the friction force influences on the flow behaviour significantly. Numerical simulations on rapid decompression process in rich and base gas mixtures were performed (Botros et al., 2007) by using the commercial one-dimensional OLGA code (SPT-group) (Bendiksen et al., 1991) as well. All predictions, which were made by using OLGA code (Botros et al., 2007), show a poor comparison with experimental data and all calculated values are significantly over-predicted.

The paper presents a one-dimensional transient mathematical model of compressible thermal multi-component gas mixture flow in pipes. Numerical analysis on rapid decompression process in a shock tube having base natural gases is performed by using the proposed mathematical model. The model is successfully validated on the experimental data on rapid decompression in base natural gas mixtures (Botros et al., 2003) and it shows a good agreement with the experiments. A proper modelling of gas mixture continuity, momentum and enthalpy equations together with taking into account the thermo-physical fluid properties (SRK–EOS) is the key to successful model performance. The proposed mathematical model predicts the decompression wave speed in base natural gases much better compared to mathematical and analytical models, which are available from the open source literature.

2. One-dimensional mathematical model of transient thermal fluid flow in pipes

The set of mass, momentum and enthalpy conservation equations is solved for gas phase in the mathematical model. This set of equations for single phase gas mixture flow in general form is written as (Wallis, 1969):

$$\frac{\partial \alpha_G \rho_G}{\partial t} + \frac{\partial \alpha_G \rho_G U_G}{\partial z} = 0 \tag{1}$$

$$\frac{\partial \alpha_G \rho_G U_G}{\partial t} + \frac{\partial \alpha_G \rho_G U_G^2}{\partial z} = -\alpha_G \frac{\partial P}{\partial z} - R_{G-Wall} \tag{2}$$

$$\frac{\partial \alpha_G \rho_G h_G}{\partial t} + \frac{\partial \alpha_G \rho_G U_G h_G}{\partial z} = \alpha_G \left(\frac{\partial P}{\partial t} + U_G \frac{\partial P}{\partial z} \right) + R_{G-Wall} U_G \tag{3}$$

Here, α_G is the volume fraction of the gas mixture; ρ_G is the density of the gas mixture; U_G is the velocity of the gas mixture; P is the total pressure; R_{G-Wall} is the friction term, h_G is the enthalpy of the fluid, t is the time, z is the axial co-ordinate. The last term in the equation of enthalpy conservation (3) represents an additional contribution into the system's enthalpy due to the friction force.

The friction term is written in the form of Blasius (1913):

$$R_{G-Wall} = \frac{\Pi}{S} \tau_{G-Wall}, \quad \tau_{G-Wall} = \frac{\xi_{G-Wall} \rho_G U_G^2}{8} \tag{4}$$

$$\begin{cases} \xi_{G-Wall} = 64/Re_G, & Re_G < 1600 \\ \xi_{G-Wall} = 0.316/Re_G^{0.25}, & Re_G > 1600 \end{cases} \tag{5}$$

$$Re_G = \frac{\rho_G U_G D_{pipe}}{\mu_G} \tag{6}$$

Here, Π is the perimeter of the pipe; S is the cross-sectional area of the pipe; τ_{G-Wall} is the friction term, which represents friction between the gas and the wall of the pipe; ξ_{G-Wall} is the friction coefficient; D_{pipe} is the diameter of the pipe; μ_G is the viscosity of the fluid.