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Leak detection of non-isothermal transient flow of hydrogen-natural gas mixture

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ABSTRACT

Transient pressure wave detection analysis to detect the location of leakage of non-isothermal flow in an inclined pipeline containing hydrogen-natural gas mixture is investigated. The governing equations are solved using the reduced order modelling technique. The effects of inclination angles, mass ratio of gas mixture and temperature change on the pressure and celerity waves in an inclined pipeline are discussed. The solutions for isothermal flow in a horizontal pipeline show good agreement with published results. For non-isothermal flow an increase in the mass ratio lead to an increase in the pressure and celerity waves, while the leak location and amount of leak discharge decrease. However, it is noted that the amount of leak discharge is still higher than that of isothermal flow. It is also observed that an increase in the inclination angle increases the pressure drop and leak discharge but the celerity wave and the leak location do not seem to be affected. Thus, to reduce the leak discharge, the inclination angle of the pipeline should be reduced and further, to ensure that leakage does not occur before the calculated leak position, the mass ratio of hydrogen to natural gas should not be more than 0.5.

1. Introduction

Gas distribution pipeline networks are systems with hundreds or thousands of kilometers of pipes which contain compression stations and other devices like valves. These types of systems work at high pressure and use compression stations to supply the gas over long distances with enough energy. In many pipeline simulations, rapid changes in the solution are present due to the disturbances generated by the fluctuations in operation of system controlling devices such as valves, compressors and pressure regulators (Chaczykowski, 2010). As a result, non-isothermal gas flow models need to be considered to account for sharp changes in the gas pressure, temperature and flow rate.

For the non-isothermal flow in a pipeline, the gas properties can be assumed to be varied or not constant over any cross section in a pipeline. When a gas mixture is subjected to a temperature change, some properties, such as the density and viscosity, will change accordingly. In some situations, these changes are large enough to have a substantial influence on the flow characteristics. Transient non-isothermal modelling of different pipeline operating conditions is widely used, especially when testing various control strategies proposed for the gas transmission system. Solution of the non-isothermal flow model requires certain types of pipeline thermal models as a component of the flow model responsible for heat flow in the gas and through the pipeline walls. Depending on the form of heat transfer term, there are two models for obtaining the amount of heat exchanged by the gas with its surrounding environment, which are steady state and unsteady heat transfer (Abbaspour and Chapman, 2008; Chaczykowski, 2010; Ebrahimzadeh et al., 2012; Osiadacz and Chaczykowski, 2001; Tentis et al., 2003). However, all these works have been considered mostly in fluids involving natural gas only but have not yet been applied in hydrogen natural-gas mixture.

Subani and Amin (2015) and Elaoud and Hadj-Taïeb (2008) studied the transient flow in hydrogen-natural gas mixtures, but they assumed that the flow is isothermal and the pipeline is laid horizontally. Later, Uilhoorn (2009) solved the gas flow of mixed hydrogen with natural gas and transport via high pressure in an inclined pipeline. Hydrogen is always combined with natural gas to enhance storage capacity, quicken burning capability and reduce air pollution (Agaie, 2014). According to Elaoud and Hadj-Taïeb (2008), during the transition period towards a full development of hydrogen market, the transmission costs by the construction of

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new network pipelines become relatively expensive. Many petroleum companies utilize the existing natural gas pipeline networks to transported hydrogen and natural gas in the same pipeline to reduce the transportation cost.

The existing pipeline is designed and constructed specifically for natural gas only. The chemical and physical properties of hydrogen differ significantly from those of natural gas. Addition of even a small quantity of hydrogen to natural gas (10%–20% hydrogen) (Veziroglu and Barbir, 1992) requires special attention especially on the leakage problem because hydrogen is a reactive gas and has high pressure (Subani et al., 2015). The problem of hydrogen or hydrogen-natural gas mixture release appears to be a major potential risk that should be predicted (Elaoud and Hadj-Taïeb, 2009; Elaoud et al., 2010).

From the 3751 pipeline incidents, that were recorded between 1994 and 1999, two third of them ware as a results of pipe leaks (Lydell, 2000). Leakage in pipelines can cause serious problems related not only to the environment or safety but also to the economy (Elaoud et al., 2010). Leaks also waste natural resources and create public health risks. Risk of leakage through pipelines is well studied for natural gas (Turner and Mudford, 1988; Wilkening and Baraldi, 2007), but not for hydrogen or hydrogen-natural gas mixtures. Subani et al. (2015), Elaoud and Hadj-Taïeb (2008) and Elaoud et al. (2010) determined the leakage of hydrogen-natural gas mixtures in pipelines, but they assumed the transient isothermal flow. They leave out the gravity and inclination terms in the momentum equation, and they do not consider the energy equation in their models.

The main objective of this paper is to determine and locate leakage on non-isothermal transient flow in the inclined pipeline system of hydrogen-natural gas mixtures based on transient pressure wave analysis. The effect of hydrogen mass ratio on the transient flow of hydrogen-natural gas mixture and leak discharge is analyzed. The effect of body force due to the inclined pipeline is also presented. The effect of temperature change on the non-isothermal flow model is determined by considering the unsteady heat transfer term in the energy equation. The transient non-isothermal flow is created by the sudden closure of a downstream shut-off valve. The governing equations are solved by the reduced order modelling (ROM) technique (Agaie and Amin, 2014; Behbahani-Nejad and Shekari, 2008, 2010; Subani and Amin, 2015; Subani et al., 2015).

2. Mathematical formulation

The governing equations consist of three coupled non-linear hyperbolic partial differential equations. The flow is assumed to be one dimensional, non-isothermal, and compressible and to include transient condition. The fluid is assumed to be a homogeneous mixture of hydrogen and natural gas.

2.1. Governing equation

From the principle of conservation of mass, momentum and energy laws, the governing equations for the transportation of hydrogen-natural gas mixtures in an inclined pipeline are given by the following:

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

$$\frac{\partial (\rho u)}{\partial t} + \frac{\partial (\rho u^2 + P)}{\partial x} + \frac{f \rho u |u|}{2D} + \rho g \sin\theta = 0 \tag{2}$$

$$\frac{\partial (\rho e)}{\partial t} + \frac{\partial (\rho u e + P u)}{\partial x} = \rho q - \rho u g \sin\theta \tag{3}$$

where ρ is defined as density, u is the gas velocity where the modulus sign is to ensure that the frictional force shall always act opposite to the direction of motion, P is the pressure, f is the coefficient of friction, D is the diameter of the pipeline, g is the gravitational force, θ is an angle between the friction force and the x direction, and q is heat transfer.

These governing equations (1) (2) and (3) will be used in transient analysis of non-isothermal hydrogen-natural gas mixture in pipeline where kinetic energy $u^2/2$ is neglected.

2.2. Equation of state

An equation of state for a gas relates the variables of pressure, density and temperature. The equation of state for perfect gas, which is commonly used in the gas industry, is given by:

$$P = \rho R T \tag{4}$$

where R is the specific gas constant and T is the temperature.

For compressible flow, the relation of equation of state with the celerity pressure wave c is denoted as:

$$P = \rho c^2 \tag{5}$$

From relation of perfect gas, the specific heat at constant volume C_v and internal energy e are defined as:

$$C_v = \frac{R}{r-1} \tag{6a}$$

$$e = C_v T \tag{6b}$$

Substituting (6a) and (6b) into (4), then the perfect gas equation is written as:

$$P = \rho C_v (r-1) \frac{e}{C_v} = (r-1)\rho e \tag{7}$$

2.3. Hydrogen-natural gas mixture equation

Density of hydrogen and natural gas is defined as:

$$\rho_h = \frac{m_h}{V_h} \text{ and } \rho_g = \frac{m_g}{V_g} \tag{8}$$

where m_g, m_h, V_g and V_h are defined as the mass of natural gas and hydrogen and volume of natural gas and hydrogen, respectively.

For hydrogen-natural gas mixtures, the hydrogen mass ratio will be used in determining the mixture density, where the mass ratio of the mixture is given as:

$$\phi = \frac{m_h}{m_h + m_g} \tag{9}$$

From the definition of density of gas, the density of hydrogen-natural gas mixture is defined as:

$$\frac{1}{\rho} = \frac{V_m}{M_m} \tag{10}$$

where $V_m = V_h + V_g$ and $M_m = m_h + m_g$.

Substituting (8) and (9) into (10), the density of hydrogen-