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A novel technique of reduce order modelling without static correction for transient flow of non-isothermal hydrogen-natural gas mixture

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ABSTRACT

In this effort towards zero carbon emission of energy generation, Hydrogen Natural Gas Mixture (HCNG) is considered as energy source. This paper focuses on transient flow of HCNG in a pipelines under non-isothermal condition, using a modern technique of Reduced Order Modelling (ROM) technique. The effect of mass ration, body force and pipeline environmental temperature profile is investigated. The pipeline surrounding temperature effect HCNG flow parameters as shown in the results. The increase in hydrogen lead to hold up, variation on pressure and celerity wave. Good agreement is observed with new method and the usual reduced order method from the solutions published. The results presented give good agreement with experimental results and the new develop model improves on the accuracy.

Introduction

As world energy requirement is continuously increases, also the search of alternation energy with aim of reducing air pollution due to energy generation. Hence, the use of hydrogen been a zero carbon emission gas is worldwide considered. These are achieved by natural gas enrichment with hydrogen gas, known as hydrogen natural gas mixture HCNG. Furthermore, there is a need of it effective transportation and the cheapest means is pipeline.

Hydrogen been the most abundant and cleanness gas in the world it consideration as a fuel alternative in our future energy demand is a clear welcome development. At standard temperature (273.15 K) and pressure (100 kPa), hydrogen is a colourless, tasteless, nontoxic and highly combustible. Hydrogen can play an important role in a sustainable energy supply, since the utilization of H_2 yields no carbon dioxide (CO_2). Hydrogen is the most common element in the universe, but it never occurs by itself on the earth. It is always combines with other elements such oxygen or carbon [23].

In many applications of gas dynamics temperature is a function of both time and space, the inclusion of energy equation in the gas flow analysis is therefore, required [22]. For effective transportation of gas in a long distance pipeline sufficient energy is required. In the process of transporting gas, energy and pressure are lost periodically and there is a need to monitor them for effective demanding capacity meet [17].

In an inviscid fluid flow analysis external work done or convective heat transfer is a dominant stage of the heat transfer mode hence one-dimensional energy conservation equation is required for effective analysis [21]. In two-phase fluid flow magnitude of change caused by transient is higher compared to single phase fluid flow [1].

Natural gas is normally operated in single phase mode initially, liquid phase are formed within the pipeline during operation due to temperature and pressure change [2]. For accurate analysis of transient flow behaviour of high pressured fluid temperature change is important. For every flow in pipelines, the pipe wall constitutes the direct neighbour of the fluid, with the exception of some cases. Generally, external heat transferred into the fluid is influenced by pipe wall [11].

Pipes are at many times in different condition due to pipeline networks design and sometimes the environmental conditions. This condition will affect the flow parameters, although at a glance it may appear to have no significant effect on flow. From the experiment result small change in fluid body force due to pipeline the inclination angle reduces pipe storage capacity and pressure drop loss, while the breakdown rate will be higher. This is as result of

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Nomenclature

e'	total energy change	m_i	mass
ρ	density of fluid mixture	n_i	polytropic index
f	coefficient of pipe friction	L	pipe length
P	pressure		
D	pipe diameter	*Subscript nomenclature*	
g	gravitational acceleration	h	hydrogen gas
θ	the pipe inclination	g	Natural gas
c	celerity wave	o	Standard condition
e	internal energy per unit mass	d	dynamic condition
h	specific enthalpy	s	steady condition
ϕ	mass ratio of HCNG		
φ	hydrogen ratio		

low gas accumulation leads to low fluid velocity [20], but more of on two phase flow analyses.

The studies of fluid properties are more accurately achieved if the reality condition of pipeline are considered [19]. Therefore there is a need for fully defining the pipeline situation in the study of HCNG transient flow. The transient behaviours of HCNG was presented on the previous published work using different numerical methods.

Governing equation

Non-isothermal conditions are governed by:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \tag{2.1}$$

$$\frac{\partial (\rho \mathbf{u})}{\partial t} + (\mathbf{u} \cdot \nabla)\rho \mathbf{u} + \nabla p = \nabla \sigma + \rho \mathbf{F} \tag{2.2}$$

$$\rho\left(\frac{\partial e' \mathbf{u}}{\partial t} + \nabla(e'\mathbf{u})\right) = \dot{Q}_g - \nabla \cdot q + \nabla \cdot (\mathbf{u} \cdot \sigma) \tag{2.3}$$

where e' is total energy change.

Numerical procedure

One dimensional flow equation is sufficient in the description of compressible gas in pipe effectively [9]. Therefore, the set of partial differential equations describing the general gas flow dynamics through a pipeline is obtained from (2.1–2.3) which are the vector for of conservation of mass, momentum and energy equations.

Hence, the one dimensional form are

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u)}{\partial x} = 0 \tag{3.1}$$

$$\frac{\partial (\rho u)}{\partial t} + \frac{\partial (\rho u^2 + \rho c^2)}{\partial x} + \frac{f \rho u |u|}{2D} + \rho g \sin\theta = 0 \tag{3.2}$$

$$\frac{\partial}{\partial t}\left[\left(e + \frac{u^2}{2}\right)\rho\right] + \frac{\partial}{\partial x}\left[\left(h + \frac{u^2}{2}\right)\rho u\right] = \rho q - \rho u g \sin\theta \tag{3.3}$$

where ρ is the density of fluid mixture, f is coefficient of pipe friction, P the pressure is equal to ρc^2, u is the velocity of fluid mixture, D is the pipeline diameter, g is the gravitational acceleration, θ is the pipe inclination and c is a celerity wave. The internal energy per unit mass is e and h the specific enthalpy.

If the kinetic energy and wave effect on temperature change are neglected Eq. (3.3) reduces into

$$\frac{\partial}{\partial t}[\rho e] + \frac{\partial}{\partial x}[\rho u e] = \rho q - \rho u g \sin\theta \tag{3.4}$$

Since the two mixed components are in gaseous form, them homogeneous mixture is assumed. For a polytropic flow the density of the resultant mixture will depend on mass ratio of each gas. To develop density of the mixture ρ of HCNG, hydrogen fluid mass ratio will be used as the determining factor of the density. Therefore, the mass ratio of the mixture is defined by

$$\phi = m_h/(m_h + m_g) \tag{3.5}$$

where ϕ, m_i are the mass ratio of HCNG, mass of hydrogen and natural gas for $i = h$ *or* g respectively.

From the definition of density of gas

$$\rho = \frac{m_m}{V_m}, \rho_h = \frac{m_h}{V_h} \text{ and } \rho_g = \frac{m_g}{V_g}$$

where V_m, V_h, V_g, ρ_h and ρ_g are volume of gas mixture.(HCNG), hydrogen and natural gas density respectively taking the reciprocal of mixture density we get

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

Furthermore, $V_m = V_h + V_g$ hence we get

$$\frac{1}{\rho} = \frac{V_h + V_g}{M_m} = \frac{m_h V_h}{M_m m_h} + \frac{m_g V_g}{M_m m_g} \tag{3.6}$$

From density definition on we get

$$\frac{1}{\rho} = \frac{1}{\rho_h}\left(\frac{m_h}{M_m}\right) + \frac{1}{\rho_g}\left(\frac{m_g}{M_m}\right)$$

Simplifying using density definition and Eq. (3.5)

$$\frac{1}{\rho} = \frac{\phi}{\rho_h} + \frac{(1-\phi)}{\rho_g}, \rho = \left[\frac{\phi}{\rho_h} + \frac{(1-\phi)}{\rho_g}\right]^{-1} \tag{3.7}$$

Assuming the flow inlet is constant under polytropic process then using polytropic index the densities of hydrogen and natural gas are expressed as:

$\frac{p}{p_0} = \left(\frac{\rho_h}{\rho_{h_0}}\right)^{n_h}$ and $\frac{p}{p_0} = \left(\frac{\rho_g}{\rho_{g_0}}\right)^{n_g}$ substituting into Eq. (3.7)

$$\rho = \left[\frac{\varphi}{\rho_h} + \frac{1-\varphi}{\rho_g}\right]^{-1} = \left[\frac{\varphi}{\rho_{h0}}\left(\frac{p}{p_0}\right)^{\frac{1}{n'}} + \frac{(1-\varphi)}{\rho_{g0}}\left(\frac{p}{p_0}\right)^{\frac{1}{n''}}\right]^{-1} \tag{3.8}$$

From the definition of celerity pressure wave and taken the derivative of (3.8) with respect to p and simplifying we have

The Celerity of pressure wave is defined as [3]: