LEAKAGE DETECTION OF TRANSIENT HYDROGEN-NATURAL GAS MIXTURE USING REDUCED ORDER MODELLING

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To my beloved papa, mama and family.

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ABSTRACT

Early detection of gas leakage and its location in a pipeline is crucial in the effort to avoid impending disasters such as pipeline rupture. Existing studies mainly use sensors to detect and determine the onset of leakage, but these sensors, depending on their types are expensive to install. They could also give rise to false alarms and their handling needs skilled operators. As such, mathematical modelling has been adopted to be a viable alternative that is highly sensitive to pinpoint the leak location even for small leaks and to minimize the occurrence of false alarms at low cost. The present investigation focused on the development of a mathematical model for transient non-isothermal flow of hydrogen-natural gas mixture in a pipeline. This mixture is considered as hydrogen is often added to natural gas to enhance the latter's burning capacity, and because hydrogen needs to be transported in the same pipeline as natural gas due to its storage problem and to reduce transportation cost. The mathematical model developed took into consideration the effect of the mass ratio of gas mixture, the transient condition due to the sudden closure of valves during leakage, the surrounding temperature and the inclination angle of pipeline. The gas mixture was assumed to be homogeneous and the transient pressure wave was created by the sudden or instantaneous closure of a downstream shut-off valve to ensure the attainment of minimum pressure at the downstream end within a short time. The boundary conditions imposed were under the assumption that a reservoir exists at the upstream and a sudden closure valve was at the downstream. The governing equations consist of non-linear partial differential equations of unsteady, compressible and non-isothermal one dimensional flow. They were numerically solved using the reduced order modelling (ROM) technique, which had not been previously applied on non-isothermal models involving gas mixtures. The transient pressure wave analysis was adopted to calculate the leak location and leak discharge. Specifically, the iron pipeline was taken to be $0.4\,\mathrm{m}$ in diameter, $600\,\mathrm{m}$ long, mass flow $Q_0 = 55\ \mathrm{kg/s}$ at a static temperature $T = 15^{\circ}\mathrm{C}$ and an absolute pressure $P = 35\,\mathrm{bar}$. Numerical results on the effects of inclination angles, mass ratio of gas mixture and temperature change on the transient pressure and celerity waves due to the inclined pipeline show that the leakage occurs at about $200\,\mathrm{m}$. It is observed that the leak position is closer to the reservoir and the amount of leak discharge is higher than that of isothermal flow. An increase in the mass ratio ϕ leads to an increase in the pressure and celerity wave, while the leak location and amount of leak discharge decrease. It is found that the mass ratio of hydrogen to natural gas should not be more than 0.5 to ensure that leakage does not occur before the estimated leak position. It is also observed that an increase in the inclination angle θ increases the pressure drop and leak discharge but the celerity wave and the leak location do not seem to be affected.

ABSTRAK

Pengesanan awal kebocoran dan lokasinya pada saluran paip adalah penting bagi mengelakkan kemungkinan berlakunya bencana seperti ledakan gas. Kebanyakan kajian sedia ada menggunakan sensor untuk mengesan dan menentukan kebocoran, walau bagaimanapun pemasangan sensor ini sangat mahal bergantung kepada jenisnya. Ia boleh mengakibatkan amaran palsu, disamping keperluan kepada tenaga mahir untuk pengendaliannya. Oleh itu, pemodelan matematik adalah alternatif yang berdaya maju dengan ketepatan yang jitu bagi menentukan lokasi kebocoran walaupun terhadap kebocoran kecil, dan kejadian amaran palsu boleh diminimumkan pada kos yang rendah. Penyelidikan ini memberi tumpuan kepada pembangunan model matematik bagi aliran campuran hidrogen-gas asli dalam saluran paip dengan suhu tak sekata. Campuran ini dipertimbangkan kerana hidrogen sering ditambah kepada gas asli untuk meningkatkan kadar pembakaran, disamping hidrogen tidak boleh disimpan dan ia perlu di angkut bersama gas asli di dalam saluran paip yang sama untuk mengurangkan kos pengangkutan. Model matematik yang dibangunkan mengambil kira kesan nisbah jisim gas campuran, keadaan fana yang disebabkan oleh penutupan injap serta-merta semasa kebocoran berlaku, suhu sekitar dan sudut kecondongan saluran paip. Campuran gas diandai sebagai homogen dan gelombang tekanan fana dihasilkan oleh penutupan injap secara tiba-tiba atau serta-merta pada hiliran paip untuk memastikan tekanan minimum tercapai pada hujung hiliran paip dalam masa yang singkat. Syarat sempadan yang dikenakan mengambil kira terdapatnya reservoir di hulu paip dan injap ditutup serta merta di hiliran. Persamaan menakluk terdiri daripada persamaan pembezaan separa tak linear, bagi aliran satu dimensi tak mantap, mampat dan suhu tak sekata. Persamaan ini telah diselesaikan secara berangka dengan menggunakan teknik pemodelan pengurangan tertib (ROM), yang mana teknik ini belum pernah digunakan pada model suhu tak sekata yang melibatkan campuran gas. Analisis gelombang tekanan fana digunakan bagi mengira lokasi dan kadar alir kebocoran. Khususnya, saluran paip besi digunakan dengan diameter $0.4\,\mathrm{m}$, $600\,\mathrm{m}$ panjang, aliran jisim $Q_0 = 55\,\mathrm{kg/s}$ pada suhu statik $T = 15^{\circ}\mathrm{C}$ dan tekanan mutlak $P = 35\,\mathrm{bar}$. Keputusan berangka terhadap kesan sudut kecondongan saluran paip, nisbah jisim campuran gas dan perubahan suhu terhadap tekanan dan halaju rambat fana yang disebabkan oleh kecondongan paip menunjukkan kebocoran berlaku di sekitar $200\,\mathrm{m}$. Lokasi kebocoran saluran gas didapati lebih dekat kepada reservoir dengan jumlah kadar alir kebocoran adalah lebih tinggi berbanding kadar alir bagi aliran suhu sekata. Peningkatan nisbah jisim ϕ menyebabkan peningkatan gelombang tekanan dan halaju rambat, manakala lokasi dan jumlah kadar alir kebocoran pula menurun. Nisbah jisim hidrogen kepada gas asli didapati tidak boleh melebihi daripada 0.5 untuk memastikan kebocoran tidak akan berlaku sebelum lokasi anggaran. Peningkatan sudut kecondongan θ juga diperhatikan akan meningkatkan penurunan tekanan dan kadar alir kebocoran, akan tetapi gelombang halaju rambat dan lokasi kebocoran tidak terjejas.

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LIST OF ABBREVIATIONS

CFD	-	Computational fluid dynamics
HNGM	-	Hydrogen-natural gas mixture
CNG	-	Compressed natural gas
HCNG	-	Hydrogen compressed natural gas mixture
CPU	-	Central processing unit
ROM	-	Reduced order modelling
FSM	-	Implicit Steger Warming flux vector splitting method
FDM	-	Finite difference method
FVM	-	Finite volume method
TVD	-	Total variation diminishing method
MOC	-	Method of characteristics
MOL	-	Method of lines
ACV	-	Automatic closure valve
RCV	-	Rapid closure valve
RTTM	-	Real time transient modelling
TDLAS	-	Tunable diode laser absorption spectroscopy
LIF	-	Laser induced fluorescence
CARS	-	Coherent anti-Raman spectroscopy
FTIR	-	Fourier transform infrared spectroscopy
LDS	-	Leak detection sensor

LIST OF SYMBOLS

ρ	-	Density (kgm^{-3})
$\mathbf{V}$	-	Vector gas velocity (-)
u	-	Flow velocity (ms^{-1})
x	-	Distance along the pipeline (m)
t	-	Time (s)
P	-	Pressure (bar)
c	-	Speed of sound in natural gas (ms^{-1})
τ_w	-	Shear force at the wall (N)
τ_x	-	Shear force at x-axis (N)
F	-	Net body force per unit mass (N/kg)
ρ_m	-	Density of gas mixture (kgm^{-3})
u_m	-	Flow velocity of gas mixture (ms^{-1})
c_m	-	Celerity waves of gas mixture (ms^{-1})
ϕ	-	Mass ratio of hydrogen and natural gas (-)
M_m	-	Mass of gas mixture (kg)
m_g	-	Mass of natural gas (kg)
m_h	-	Mass of hydrogen (kg)
m_m	-	Mass of gas mixture (kg)
m	-	Mass flux ($kgm^{-2}s^{-1}$)
V_m	-	Volume of gas mixture (m^3)
V_g	-	Volume of natural gas (m^3)
V_h	-	Volume of hydrogen (m^3)
m_c	-	Types of valve closing curve (-)
n'	-	Index number of hydrogen (-)
n''	-	Index number of natural gas (-)

g	-	Gravitational force (ms^{-2})
θ	-	Angle between the force vector F and the x - direction (^{o})
D	-	Internal diameter of the pipeline (m)
f	-	Coefficient of pipe friction (-)
k	-	Thermal conductivity (-)
e	-	Internal energy (J/kg)
ε	-	Heat flux ($Jm^{-2}s^{-1}$)
q	-	Heat transfer (-)
z	-	Compressibility factor (-)
R	-	Universal gas constant (-)
T	-	Gas temperature (K)
C_p	-	Specific heat at constant pressure (J/kgK)
C_v	-	Specific heat at constant volume (J/kgK)
μ	-	Viscosity (Nsm^{-2})
τ	-	Time of valve closing (s)
A	-	Area of pipeline leak (m^2)
A_ℓ	-	Orifice area of pipeline (m^2)
L	-	Length of pipeline (m)
X_L	-	Length of leakage point (m)
Q_ℓ	-	Internal discharge flow (m^3s^{-1})
Q_L	-	Amount of leak discharge (kgs^{-1})
C_d	-	Discharge coefficient (-)
A_M	-	Jacobian matrix of flux vector E (-)
B_M	-	Jacobian matrix of flux vector H (-)
I	-	Identity matrix (-)
Z	-	Diagonal matrix (-)
X	-	Eigenvector matrix (-)
E , H	-	Homogeneous flux vector (-)

Subscripts:

1	-	Point at upstream the leak (-)
2	-	Point at downstream the leak (-)
s	-	Condition of constant entropy (-)
S	-	Quasi steady matrix (-)
d	-	Systems dynamic matrix (-)

M	-	Matrix (-)
m	-	Mixture (-)
h	-	Hydrogen (-)
g	-	Natural gas (-)
L	-	Leak (-)
p	-	Pressure (-)
v	-	Volume (-)

Superscripts:

0	-	Steady state (-)
T	-	Transpose (-)

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CHAPTER 1

INTRODUCTION

1.1 Research Background

In general, transportation in a pipeline is among the biggest infrastructure projects in developing countries in recent years. Liquids and gases are transported in pipelines and any chemically stable substance can be sent through a pipeline. These liquids and gases can be delivered to consumers, whether in different countries, towns or villages. There are many types of fluid or sources that can be transported through a pipeline such as oil, biofuel, ammonia, coal, hydrogen and the common one is natural gas.

Three major types of pipelines are found along the transportation of natural gas from the point of production to the point of use, which are gathering pipelines, transmission/transportation pipelines and distribution pipelines [refer to Figure 1.1] (Shaw, 2012). Gathering pipeline systems gather raw natural gas from production wells and transport it to centralized points, such as processing facilities, tanks, or marine docks. Transportation pipelines carry natural gas across long distances and occasionally across interstate boundaries, usually to and from compressors or to a distribution center or storage facility. Distribution pipeline systems can be used to transport natural gas to homes and businesses through large distribution lines mains and service lines.

In this research, the transportation of hydrogen-natural gas mixture in an inclined pipeline is considered. Transportation pipelines are used to transport crude oil and natural gas from their respective gathering systems to refining, processing, or storage facilities. It also transports refined petroleum products and natural gas to customers, for use and further distribution. Transportation pipeline systems include all of the equipment and pipeline components to facilitate the transportation of the products. This includes the pipe, valves, pumps or compressors, tanks, refining and processing facilities and other equipment and facilities. Transportation pipelines are constructed from steel pipe as diameters of pipe commonly used range in size from $4\,\text{in}$ to $48\,\text{in}$ and can range in length from $101\,\text{cm}$ to $121\,\text{cm}$ (Baker and Fessler, 2008; Baum, 1996; Shaw, 2012). In the transportation pipeline, the fluid could be a single phase, liquid phase or gas phases. It is could be the mixture of gas, liquids or may be solid.

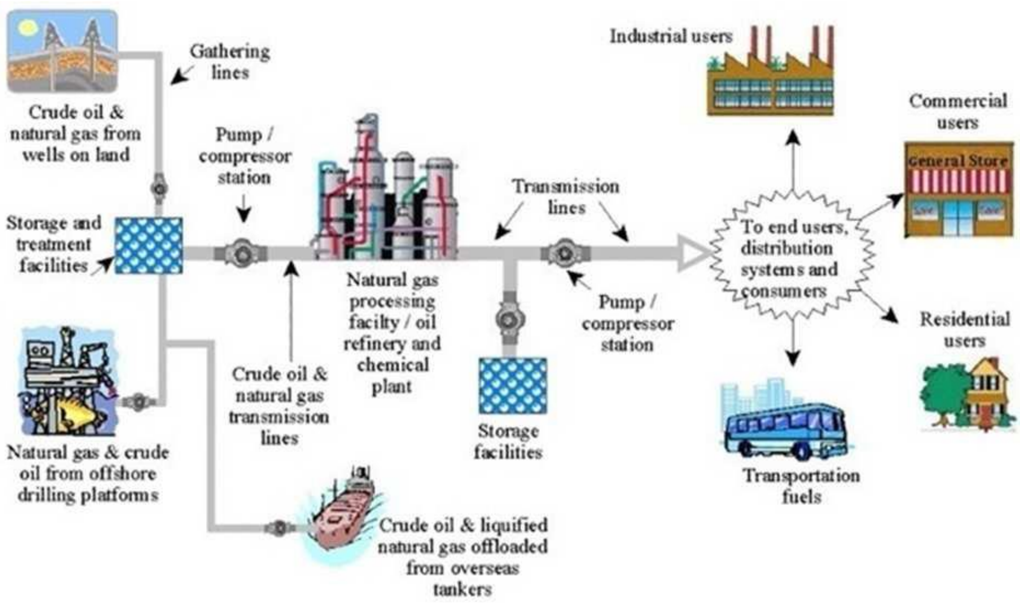

Figure 1.1 Types of natural gas pipeline (Shaw, 2012)

Commonly, only one gas which is natural gas could be considered in simulating the transient flow in a pipeline. Natural gas is a combustible gas, hydrocarbon mixture which is predominantly 85% of methane, 10% of ethane and small amount of propane, butane and nitrogen (Kidnay and Parrish, 2006). Natural gas could also refer as compressed natural gas (CNG). Natural gas has promising energy source with less carbon emission output when compared to coal and petroleum oil (Younger, 2004). To reduce carbon emission, attention has been put on energy generation through natural gas. Natural gas is easier to store and transported through the pipeline (Bade and Karim, 1999; Balat and Balat, 2009; Elaoud and Hadj-Taïeb, 2008; Hoeseldonackx and D‘haeseleer, 2011; Uilhoorn, 2009; Veziroglu and Barbir, 1992). However, natural gas has the low burning velocity capacity and poor lean capability (Cheng *et al.*, 2009; Tabkhi *et al.*, 2008).

During the transition phase towards a full development of hydrogen market, the use of the existing natural gas network, mixed with hydrogen or often known as hydrogen-natural gas mixture seems to be a good economic solution (Bade and Karim, 1999; Geagla *et al.*, 2013; Karim *et al.*, 1996; Ma, *et al.*, 2009). Hydrogen could play an important role as a sustainable energy supply (Corbo *et al.*, 2011; Elaoud and Hadj-Taïeb, 2008; Subani *et al.*, 2015; Uilhoorn, 2009). Hydrogen is an attractive, colourless, non-toxic and clean flammable gas and it’s considered as a future energy source (Corbo *et al.*, 2011; Winter, 2009). If hydrogen is made from renewable energy sources without yielding much carbon dioxide (CO_2), it would be possible to produce and use energy with near zero emissions of greenhouse gases or air pollutants (Srinivasan and Ogden, 2006).

Adding a small percentage of hydrogen will not only quicken the burning capacity of other gases, but it is also environmentally friendly since it has zero emission (Ma *et al.*, 2009). However, hydrogen has a storage problem and it does not exist on its own (Sierens and Rosseel, 2000), but it could be manufactured (Balat and Balat, 2009). It occurs chiefly in combination with other gases such as natural gas, which will improve its performance (Bade and Karim, 1999; Balat and Balat, 2009; Elaoud and Hadj-Taïeb, 2008; Hoeseldonackx and D‘haeseleer, 2011;

Uilhoorn, 2009; Veziroglu and Barbir, 1992). The mixture of hydrogen and natural gas occurs either through pipeline transportation or by injecting (Cheng *et al.*, 2009; Tabkhi *et al.*, 2008). Transmission costs of the construction of new networks of pipelines exclusively for transporting hydrogen will be relatively expensive (Elaoud and Hadj-Taïeb, 2008). Thus, hydrogen is usually transported in the same pipeline as natural gas to reduce the transportation cost, to enhance the storage capability and to increase the storage problem.

According to Veziroglu and Barbir (1992), the transportation of natural gas and hydrogen is feasible as long as the mass ratio of hydrogen remains sufficiently low. From the experimental results, the mass ratio is in the range of 10% to 20% hydrogen by volume mixed with natural gas. The addition of even a small quantity of hydrogen to natural gas may have an impact on the safety related to the delivery of gas and to the economics of the country. 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). Mixing higher percentages of hydrogen requires special attention regarding the functioning of pipeline, end-user appliances and emissions (Uilhoorn, 2009). Hydrogen is a reactive element and it diffuses into the materials such as the steel pipelines and this could cause changes in the mechanical properties and could lead to rupture or leakages.

Leakage detection is very important to consider because pipelines contain hazardous and flammable gas and its potential hazards. Leakage in pipelines, can cause serious problems related not only to the environment or safety, but also the economy (Elaoud *et al*., 2010). Leaks also waste natural resources and create a public health risk. Leakage in a pipeline can cause from the pipeline, third party and from natural disaster. The accident of a pipeline may come from a chemical reaction resulting in internal corrosion. From the third party, the pillar drill or heavy machine use to hammer the ground may disturb the pipe. The severe earthquake and the land subsidence can also cause serious damage to the pipe.

Figure 1.2 Gas leakage on natural gas pipeline (courtesy of Doug, 2014)

During the construction and operation, the pipelines must be able to withstand a variety of loads and ranging from the high loads because the major cases in most pipelines is that the cause of the internal pressure. Third party damage also included in pipelines failures categories that will cause a big implication to industry. Generally, there are many factors that will give a big impact to the pipeline transportation. For example, in oil and gas industry, non-homogeneous mixture, corrosion and also leakage problems could be happened in the pipeline (Khare and Singh, 2010). Figure 1.2 shows the gas leakage occurs on natural gas pipeline.

There are two main types of methods can be used to detect leakage in pipelines which divided into hardware-based and software-based. Hardware-based methods rely mainly on the use of special sensing devices to detect fluid leakage. It is depending on the type of sensors and equipment used for detection. Hardware-based methods are able to detect very small leaks and the leak location, but installations of the sensors for these methods are very expensive and the detection time is very long. To overcome these difficulties, the mathematical modelling to determine leakage in gas pipeline should be focussed. Software-based methods have software programs which based on the mathematical modelling. The implemented algorithms continuously monitor the state of pressure, temperature, flow rate and other pipeline parameters (Jin *et al*., 2014). The algorithms can conclude if a leak has occurred based on the evolution of these parameters.

In this thesis the leakage detection of hydrogen-natural gas mixture can be done by using a technique of transient pressure wave analysis. The governing equations can be solved numerically by using Reduced Order Modelling (ROM) technique. The Implicit Steger-Warming Flux Vector Splitting method is interested to consider as one of the schemes in ROM technique to solve the governing equations. ROM was proposed by Behbahani-Nejad and Shekari (2010) and was used to analyse on the transient gas flow in a rigid pipeline. Thus, the MATLAB programming will be developed to solve the governing equations to analyse the behavior of the flow characteristics of hydrogen-natural gas mixture in a pipeline when the leakage occurs.

1.2 Problem Statement

Detection of leakage and its location has always been one of the main problems in gas pipeline transportation. Early detection is crucial to avoid impending disasters. Previous study only focusing on the external/hardware-based method to determine leak in pipelines. The external methods of leak detection, especially from the natural gas pipelines include the optical method with potential sensors such as the lidar absorption, diode laser absorption, broadband absorption, backscatter imaging, thermal imaging and multi-spectral imaging (Ikuta *et al*., 1999; Kulp *et al*., 1993; Minato *et al*., 1999; Spaeth and O'Brien, 2003). It is observed that detecting leakage in pipelines using detection sensors, especially for underground pipelines is difficult depending on the types of sensors and equipment used and these are usually expensive. The suitable technique has been chosen to determine and locate leakage in gas pipeline (Oke *et al*., 2003). The internal/software-based methods are the method used to detect and locate leaks based on mathematical modelling. One of the internal methods is a transient pressure wave analysis.

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 mixture. In the gas pipeline transportation system, the existing pipe is designed and constructed specifically for natural gas only. A study on the transportation of hydrogen-natural gas mixture in the existing pipeline is important, because the chemical and physical properties of hydrogen differ significantly from natural gas. The pressure evolution of hydrogen-natural gas mixture during the transient flow will not be the same (Veziroglu and Barbir, 1992). It is not at all possible to simply replace natural gas by hydrogen in the existing natural gas pipeline (Elaoud and Hadj-Taïeb, 2008; Tabkhi *et al*., 2008). The mass ratio of the gas mix has not been correctly predicted. Since hydrogen is a reactive gas, it can cause changes in the mechanical properties and could lead to leakage. Therefore, the mass ratio portion of both gases is important to consider to prevent the pipeline rupture.

Valves are always installed in the pipeline to control the gas flow when damage occurs. Maximum pressure can occur during the valve closure or at the end of the closure operation. Short times during valve closure are important in reducing the maximum pressure, especially in emergency conditions, especially when leakage occurs (Karney and Ruus, 1985; Subani and Amin, 2015). Previous study only considers the linear closing valve law and most studies assumed the flow to be at steady state conditions. Study on transient condition is important because pipeline flows are frequently in unsteady state due to the sudden opening and closing of valves. To reduce the pressure, sudden or instantaneous closure valve will be considered to ensure the attainment of minimum pressure at the downstream end within a short time. Thus, the effect of the sudden closure valve is important to investigate.

In many pipeline simulations, the flow characteristics are changing due to the operation of system controlling devices such as valves, compressors and pressure regulators (Chaczykowski, 2010). As a result, non-isothermal gas flow models are used, to account for sharp changes in the gas pressure, temperature and flow rate. Many researches on the gas flow assumed that the temperature is constant through the pipeline, thereby they are neglecting the energy equation. But, in most cases, the isothermal flow is not an accurate assumption, due to the fact that heat transfer changes the gas temperature as it travels through the pipeline. One very important outcome of this reality, the non-isothermal flow will be considered. 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 and some properties, such as the density and velocity, will change accordingly (Abbaspour and Chapman, 2008; Tentis *et al*., 2003).

Another problem is the position of the pipeline. Most analysis of flow in pipeline system has assumed the pipeline is laid horizontally (Behbahani-Nejad and Shekari, 2008; 2010; Elaoud and Hadj-Taïeb, 2008; Zhou and Adewumi, 1995). In the engineering design of pipeline networks, the pipeline is not always placed horizontally or lie at the same height. From experiments conducted on the effect of the inclination angle of pipelines, reduced storage capacity and pressure loss have been observed (Lubbers, 2007). The inclination term should be included in the models because the pressure drop along the pipe has a strong dependence on inclination term (Herr´an-Gonz´alez *et al*., 2009). It is important to determine the effect of body force due to the inclined pipeline in order to give more accurate and real representation of pipeline systems.

Based on these problems, this study is therefore conducted where the leak location and leak discharge will be calculated based on the transient pressure wave analysis for non-isothermal flow of hydrogen-natural gas mixture in an inclined pipeline.

1.3 Objectives of Research

The main objective of this research is to develop a mathematical model and numerical code to calculate the leak location and leak discharge for transient non-isothermal flow of hydrogen-natural gas mixture. The specific objectives are:

1. To determine the effect of mass ratio of gas mixture on the flow characteristics of hydrogen and natural gas at leakage point.
2. To determine the effect of sudden closing valve on the flow characteristics of gas mixture at leakage point.
3. To evaluate the effect of inclination angle in a pipeline on the flow characteristics of gas mixture at leakage point.
4. To investigate the effect of temperature change on the flow characteristics of gas mixture at leakage point.

1.4 Scope of Research

This research focuses on the one dimensional flow system with a homogeneous gas mixture of hydrogen and natural gas. The flow is assumed to be compressible and inviscid (viscosity of gases are neglected). The viscosity of hydrogen and natural gas are neglected because they are very small, which are 0.88×10^{-5} kg/ms and 1.10×10^{-5} kg/ms for hydrogen and natural gas, respectively. The transient will occur due to the sudden closing of valve at the downstream end of the pipeline. The Reduced Order Modelling (ROM) will be used as the numerical technique for solving the governing equations. The application will be considered in the transportation of hydrogen-natural gas mixture which includes the effect of mass ratio of hydrogen and natural gas, sudden closing valve, inclination angle, temperature change and the leakage detection in the rigid gas pipeline. The leakage causes from the internal pressure since hydrogen will be mixed with natural gas in the same pipeline. Non-isothermal flow will be considered to determine the leak point in the inclined pipeline based on the analysis of the transient pressure wave.

1.5 Significance of Research

This study concerns the transportation of hydrogen-natural gas mixture through a pipeline (Bade and Karim, 1999; Balat and Balat, 2009; Cheng *et al.*, 2009; Elaoud and Hadj-Taïeb, 2008; Hoeseldonackx and D‘haeseleer, 2011; Tabkhi *et al.*, 2008; Uilhoorn, 2009; Veziroglu and Barbir, 1992). Mixing hydrogen into the existing natural gas pipeline has increased the output of renewable energy systems such as wind farm and reduce the greenhouse emission (Bade and Karim, 1999; Geagla *et al*., 2013; Karim *et al.*, 1996; Ma, *et al.*, 2009). A large wind farm may consist of several hundred individual wind turbines or wind power which are considered to be plentiful, renewable, widely distributed, clean and zero greenhouse gas emitting during operation. By mixing hydrogen into the natural gas pipeline, the transportation and storage capacity of the existing infrastructure can be used directly to consumers. Transportation of hydrogen-natural gas mixture through pipeline can contribute significantly to solve the problem of transporting and storing electricity which generated from renewable resources. Therefore, this study would help other researcher to focus on their studies to develop an efficient pipeline distribution.

Pipeline companies are facing a major challenge to detect and locate leakages. This study contains a comprehensive review of the techniques used in detecting and locating gas leaks (Hunaidi and Chu, 1999; Hunaidi *et al*., 2000; 2004; Ikuta *et al*., 1999; Iseki *et al*., 2000; Minato *et al*., 1999; Oke *et al*., 2003; Sivathanu and Gore, 1991; Sivathanu *et al*., 1991). It is difficult to secure a pipeline with many leakage detection sensors, especially for underground pipelines. Installation of the sensors into pipeline are very expensive and the detection time is very long. To solve the leakage problem, sophisticated leak detection techniques are required (Jin *et al*., 2014). In this study, the best method for leakage detection is proposed based on mathematical modelling, which is the transient pressure wave analysis technique (Brunone *et al*., 2000; Elaoud and Hadj-Taïeb, 2009; Elaoud *et al*., 2010; Ivetic and Savic, 2007). This method is more significant and correctly simulates transient flow with the presence of leaks. Thus, this study will give the ideas for the other researchers who interested to study the leakage detection in the future.

In this study, Reduced Order Modelling (ROM) technique is developed for solving the transient flow (Behbahani-Nejad and Shekari, 2010). This method will be modelled and applied to reduce the simulation time of unsteady flow models (Behbahani-Nejad and Shekari, 2008; 2010; Dowell, 1996; Florea *et al*., 1998; Hall, 1994; Romanowski and Dowell, 1997). This method is a new application for the transportation of transient flow of hydrogen-natural gas mixture problems. However, this method is an efficient computational method to solve the transient flow in gas pipelines. This method gives minor errors and can be reduced the computational cost compared to the other method such as method of characteristics, finite difference method or method of lines. This study will provide a platform for other researcher to explore into unsteady or transient flow problem, especially in the scope of ROM technique, and in oil and gas industry.

1.6 Outline of Thesis

This thesis is divided into seven chapters, including this introduction chapter. The present chapter brief the introduction on the leakage detection of transient hydrogen-natural gas mixture in a pipeline. All the problems in this study are based on hydrogen-natural gas mixture. The justification of the study is presented in the problem statement section, followed by the research objectives. The scope and importance of the study are also highlighted at the end of this chapter. The remainder of the thesis is organized in six chapters.

In Chapter 2, the literature review is presented. The chapter starts with the importance of hydrogen-natural gas mixture. Then, the previous review of one dimensional gas flow models in a pipeline. Various mathematical models of gas flow in a pipeline are reviewed, which include the continuity, momentum and energy equations. Some techniques to detect and locate leaks in a pipeline are also discussed in this chapter, such as external methods (hardware-based methods) and internal methods (software-based methods). The advantages and disadvantages of each method are also presented. The numerical method is a very important part to consider in solving and simulating this transient flow. In this chapter, some of numerical methods such as finite difference method, characteristics method, method of lines and reduced order modelling are also presented for solving the gas flow analysis in a pipeline.

Chapter 3 presents the mathematical modelling of the leakage detection on non-isothermal transient flow of hydrogen-natural gas mixture in an inclined pipeline. The governing equations consist of non-linear hyperbolic partial differential equations which are continuity, momentum and energy equation are presented with the boundary and initial conditions. The equations of mass ratio, density and celerity wave of hydrogen-natural gas mixture, and sudden closing valve equation are also given in this chapter. The formulation to calculate the leakage position and leak discharge are given at the end of this chapter.

In Chapter 4, the solution procedure of Reduced Order Modelling (ROM) technique is discussed in detail. The governing equations are numerically solved using Implicit Steger-Warming Flux Vector Splitting Method (FSM) scheme. The procedure to determine the eigenvalues and the eigenvectors are also presented. In this chapter, the FSM and ROM algorithm are developed to carry out the numerical computation of the non-isothermal flow and presented at the end of this chapter.

In Chapter 5, the results on the leak location and leak discharge for isothermal flow is presented. The numerical results obtained have been presented and validated with existing numerical methods for pressure behavior on isothermal flow of the gas mixture in a horizontal pipeline. The new results are presented by considering the effects of sudden closing valve, mass ratio of hydrogen and natural gas and inclination angles for isothermal flow in an inclined pipeline. Results on the pressure and celerity wave are used to determine the leak location and the leak discharge of hydrogen-natural gas mixture on isothermal flow in a pipeline.

Chapter 6 determines the effect of temperature change on the flow characteristics of hydrogen-natural gas mixture. The parameters such as properties of hydrogen and natural gas, diameter and length of pipeline, and the governing equations, boundary and initial conditions are remain same as Chapter 5. The results for non-isothermal flow is validated and compared with the isothermal flow in Chapter 5. The effect of temperature change for non-isothermal flow is discussed in detail in this chapter.

Finally, Chapter 7 contains some concluding remarks, summary of research, several recommendations for future works are suggested and our achievements in this research.

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