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Unsteady natural gas flow within pipeline network, an analytical approach

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ABSTRACT

The natural gas pipeline network (including distribution network) may be subjected to some extreme conditions such as pipeline rapture, sudden changed demand and etc. The behavior of natural gas pipeline network should be properly identified to prevent network failure and have continued pipeline operation under these extreme conditions. These conditions usually cause unsteady behavior of the pipeline network. Consequently, it is necessary to develop an unsteady state mathematical method to study natural gas pipeline network under unsteady conditions. To achieve this goal, an analytical approach has been developed to analyzed natural gas pipeline network. The governing equations derived for one-dimensional isothermal compressible viscous flow with Kirchhoff's laws have been employed to develop a method for studying the pipeline network under unsteady conditions. The proposed method has been compared with previous studies for validation purposes. The validation shows the proposed method has an average absolute present derivation (AAPD) less than 0.7%. Finally the effect of a few parameters including: friction factor, natural gas composition and decreasing and increasing demand have been studied. Results show that Weymouth and AGA equation predict highest and lowest pressure drop at the network nodes respectively. Also by increasing natural gas molar mass, the pressure at nodes will be decreased. It could be also concluded that demand rise causes pressure drop to decrease and demand fall causes pressure drop to increase.

1. Introduction

Natural gas transmission and distribution pipeline network are utilized to deliver natural gas from the production points to the consumers. Unlike the other networks (electric and water distribution networks), the interruption in natural gas delivery system may have devastating effects. To prevent the interruption, the behavior of the natural gas under various conditions should be thoroughly known. To know the natural gas network behavior, it is necessary to simulate and analyze the pipeline network. Many researchers have modeled the pipeline and pipeline networks under steady state and unsteady state conditions. Due to existing of measuring devices, valves and possible accidents in pipelines and networks, the unsteady models is more close to reality than steady model. The main priority in the pipeline network modeling is to calculate volumetric flow rate in pipeline and pressure at the network nodes (or pressure drop in pipeline). Consequently, researchers are always looking for a way to calculate the volumetric flow rate and pressure, and the relationship between these two parameters.

Computing the volumetric flow rate in the steady state condition for a pipeline has been given in various publications. Weymouth (Weymouth, 1912) was the first who presented an equation to calculate volumetric flow rate and pressure drop in horizontal and inclined pipelines. Most recently, Tian and Adewumi (Tian and Adewumi, 1994) reported an analytical steady state flow equation without neglecting the kinetic energy term in the momentum equation. Zhou and Adewumi (Zhou and Adewumi, 1998) also presented an analytical flow equation for steady state flow through natural gas pipelines without neglecting any terms in the momentum equation. The well-known equations for flow equations in the steady state condition are included: Weymouth, Panhandle A & B, American Gas Association (AGA) and Colebrook-White. These equations are very practical and have been used widely in the natural gas industry. Stoner (Stoner, 1969) also presented new solutions for natural gas pipeline equations. In the Stoner study, the

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mathematical model of a system consists of node continuity equations which are solved by the dimensional Newton-Raphson Method. In one new research, Farzaneh-Gord et al. (Farzaneh-Gord et al., 2013) studied the effects of natural gas hydrate on the underground transmission pipeline in the steady state condition. In their study, the effect of natural gas composition has been also studied.

For unsteady (transient) flow in natural gas pipelines many researchers have been reported algorithms and numerical methods to solve governing equations such as: finite difference (implicit and explicit), method of characteristics and similar methods (Wylie and Streeter, 1978; Luongo, 1986; Yow, 1971; Osiadacz, 1983; Ibraheem and Adewumi, 1996; Greyvenstein, 2002). Though, all of these reported methods are time-consuming especially for analyzing pipeline network. The mentioned method (such as CFD methods) spent a lot of time to solve the governing equation and relatively has a high CPU time to analyze a single gas pipeline (Wang et al., 2015). Consequently, for a complex gas pipeline network, it can be very time consuming. Therefore, some of the researchers applied other methods to provide simpler solutions. Luongo (Luongo, 1986) and Wylie et al. (Wylie et al., 1971) linearized partial differential set of equations by neglecting the inertia term in momentum equation. Yow (Yow, 1971) formulated the transient flow problem including the inertial multiplier by the characteristics method. Osiadacz (Osiadacz, 1987) simulated transient gas flow with isothermal assumption without neglecting any terms in momentum equation for gas networks. Kiuchi (Kiuchi, 1994) analyzed unsteady gas network with isothermal conditions by applying implicit finite difference method. In Kiuchi study, the inertia term of momentum equation was neglected (Kiuchi, 1994). Dukhovnaya and Adewumi (Dukhovnaya and Adewumi, 2000) and Zhou and Adewumi (Zhou and Adewumi, 1996) simulated non-isothermal transient flow of gas in pipelines. These researches were applied total variation diminishing (TVD) scheme to formulated system of governing equations. Osiadacz and Chaczykowski (Osiadacz and Chaczykowski, 2001) compared isothermal and non-isothermal pipeline gas flow models in the unsteady conditions. Tentis et al. (Tentis et al., 2003) have used an adaptive method of lines to simulate the transient gas flow in pipelines. Gato and Henriques (Gato and Henriques, 2005) simulated unsteady, one-dimensional compressible flow in natural gas pipeline using the Runge–Kutta discontinuous Galerkin method, with third order approximation in space and time. Chaczykowski (Chaczykowski, 2009, 2010) studied sensitivity of model to the selection of the equation of state and also investigated the effect of thermal model for analyzing unsteady gas pipelines. Adeosun et al. (Adeosun et al., 2009) developed Weymouth equations for unsteady gas volumetric flow rate in horizontal and inclined pipelines. Also Olatunde et al. (Olatunde et al., 2012) presented direct calculations method of Weymouth equations for unsteady gas volumetric flow rate with different friction factors in horizontal and inclined pipelines. Ebrahimzadeh et al. (Ebrahimzadeh et al., 2012) simulated transient gas flow using the orthogonal collocation method. Their method were simulated successfully the isothermal and non-isothermal unsteady flow in gas transmission systems. Helgaker et al. (Helgaker et al., 2014) simulated one-dimensional compressible flow of natural gas pipelines using GERG 2004 equation of state. Wang et al. (Wang et al., 2015) compared four forms of hydraulic equation of a natural gas pipeline based on linearized solution from the point of view the accuracy and efficiency.

Steady state analysis of volumetric flow rate and pressure drop in pipeline network has been studied extensively in literature. Ferguson (Ferguson, 2002) and Ohirhian (Ohirhian, 2002) reported solution techniques for steady state pipeline network analysis. Their studies presented a new method according to the hydraulic equation of pipeline also nodes and close loops of pipeline network. Rios-Mercado et al. (Ríos-Mercado et al., 2002) presented a reduction technique for solving natural gas transmission network optimization problems. Their results are valid for steady-state compressible flow through a network pipeline. Abd Majid (Woldeyohannes and Majid, 2011) developed a simulation model for the steady state analysis of transmission pipeline network system (TPNS) with detailed characteristics of compressor stations. Brikic (Brikić, 2011) solved a looped gas pipeline network according to principles of Hardy Cross method for determination of appropriate friction factor and selection of a representative equation for natural gas flow. El-Shiekh (El-Shiekh, 2013) presented a mathematical formula to design natural gas transmission pipelines in the steady state condition. Natural gas network have been optimized to select the optimum diameter, number of compressor stations, length between each two compressor stations, suction and discharge pressures at compressor stations.

All of the above researches focus on simulations of gas pipeline network (transmission and distribution) in the steady state conditions. There have been limited researches in the field of unsteady (transient) gas pipeline network modeling. Tao and Ti (Tao and Ti, 1998) and Ke and Ti (Ke and Ti, 1999) presented an electrical analogy method to analyze isothermal unsteady gas flow in the natural gas pipeline network. Reddy et al. (Reddy et al., 2006, 2006) simulated transient flow in natural gas pipeline networks using a transfer function model. Accuracy and computational efficiency of their method are evaluated by comparing results with those obtained using a fully nonlinear second order accurate finite difference method. Gonzales et al. (Gonzales et al., 2009) modeled and simulated the gas distribution pipeline network. Their study was presented two numerical schemes and a MATLAB-Simulink library to solve the system proposed numerical schemes. In the recent study, researchers applied new methods that have simpler and shorter time to simulate the gas pipeline network. Behbahani-Nejad and Bagher (Behbahani-Nejad and Bagheri, 2010) presented an efficient method for transient flow simulation of gas pipelines networks. Their method was based on the transfer function models and MATLAB-Simulink. Results showed that the proposed simulation method has a sufficient accuracy and it is computationally more efficient than the other methods. Behbahani-Nejad and Shekari (Behbahani-Nejad and Shekari, 2010) proposed a reduced order modeling approach for natural gas transient flow in pipelines. They derived the linearized form of the Euler equations and obtained the corresponding Eigen system. Then, they used a few dominant flow Eigen modes to construct an efficient reduced-order. Alamian et al. (Alamian et al., 2012) proposed a method based on the state space model to simulated transient flow for gas pipelines and networks. Their results compared with those of the conventional finite difference schemes such as total variation diminishing algorithms, method of lines, and other finite difference implicit and explicit schemes. Ahmadian Behrooz and Bozorgmehry (Ahmadian Behrooz and Bozorgmehry Boozarjomehry, 2015) developed a robust general simulation framework for natural gas transmission networks. The non-isothermal models of natural gas in pipelines and governing equation for gas transmission network have been solved efficiently using the orthogonal collocation method.

As discussed, the natural gas pipeline network consists of so many pipes and nodes which make it difficult to be simulated by a computational fluid dynamics method. Also, due to possible creation of some extreme boundary conditions within the pipeline network, it is necessary to model the network under unsteady state conditions. For this purpose, in the current study, a new equation for analyzing flow of natural gas within a pipeline has been developed. The equation is derived from fundamental governing