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Development of natural gas flow rate in pipeline networks based on unsteady state Weymouth equation

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ABSTRACT

The lack of attention to unsteady state condition in pipeline networks results a considerable error for gas researchers. Our work aims to fill this gap for pipeline networks in series, parallel and looped based on unsteady Weymouth equation. For this, we introduced "Gain Coefficient" as the scale of gas flow increases in pipelines. Our results showed the gain coefficient for steady flow in series was a function of diameter and length ratios (D_2/D_1, L_1/L). The value of gain coefficient for unsteady flow closes to steady flow in series until it reaches to 1.97 after 500 h for $L_1/L = 0.25$ and $D_2/D_1 = 2.5$. Based on our development, the gain coefficient just was a function of diameter ratio for steady flow in parallel systems. According to our results, the value of gain coefficient for unsteady flow tends towards steady flow in parallel until it reaches to 12.50 for ratio of diameters equal 2.5 after 4000 h. For looped systems, fractions of looping and diameter ratio were main parameters of gain coefficient. Also, for all diameter ratios, a significant growth occurs in gain coefficient for unsteady flow when fraction of looping exceeds from 0.75. Based on our results, for fraction of looping equal to 0.75, gain coefficients for steady and unsteady flows converged to 1.94 for diameter ratio equal to 2.5 after 200 h. From our results, parallel system has a considerable preference in comparison with series and looped systems, but, it needs a large amount of cost. This paper as a basic report tries to help engineers of gas industry to design more accurate gas pipeline networks.

1. Introduction

There is a forthcoming need to transport huge quantity of natural gas from reservoirs to consumption centre. The challenging question is how to expand and operate the network in order to facilitate the transportation of specified gas quantities at minimum cost. It is possible to solve this problem using optimization of pipeline networks. Transportation of compressible natural gas through pipelines has been studied by several researchers under steady-state condition (Weymouth, 1912; Kolomogorov and Fomin, 1957; Stoner, 1969; Ikoku, 1984; Katz and Lee, 1990; Tian and Adewumi, 1994; Zhou and Adewumi, 1998; Ferguson, 2002; Ohirhian, 2002; Borraz-Sánchez and Ríos-Mercado, 2005; Ríos-Mercado et al., 2006; Wu et al., 2007; Adeosun et al., 2008; Bermúdeza et al., 2015). Practical transportation equations for steady-state gas flow are those of Mueller, Panhandle A, Panhandle B, American Gas Association (AGA), and Weymouth (Coelho and Pinho, 2007). Most of the flow equations have been derived from Bernoulli's equation (White, 1999). As the Weymouth equation is commonly used for high pressure, high flow rate, and large diameter gas gathering systems, therefore, in this research we would only consider Weymouth equation. There are some assumptions in Weymouth equation such as no kinetic energy change, no mechanical work, isothermal flow, constant compressible factor, and steady flow (Osiadacz and Chaczykowski, 2001; Langelandsvik et al., 2005; Shashi Menon, 2005; Davidson et al., 2006; Coelho and Pinho, 2007; Kabirian and Hemmati, 2007; Abbaspour and Chapman, 2008; Chaczykowski, 2009, 2010; Hamedi et al., 2009; Olatunde et al., 2012; Farzaneh-Gord and Rahbari, 2016). These consumptions can affect the accuracy of a result. Tian and Adewumi (1994) and Zhou and Adewumi (1998) modified Weymouth equation through filling some gaps in momentum equation. Tian and Adewumi (1994) presented an analytical steady-state flow equation considering the kinetic energy term in the momentum

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Nomenclature

P_i	Inlet pressure, psia
P_f	Outlet pressure, psia
T_b	Base temperature, R
P_b	Base pressure, psia
$\overline{T}$	Average flowing temperature, R
f	Moody friction factor
$\overline{Z}$	Gas deviation factor at average flowing temperature and average pressure
D	Inside diameter of pipe, in
L	Length of pipe, miles
Δt	Change in time
γ_g	Gas specific gravity (air = 1)
Q_N	Volumetric gas flow rate for pipeline network, $\frac{ft^3}{h}$ at P_b and T_b
Q_1	Volumetric gas flow rate for a single pipeline, $\frac{ft^3}{h}$ at P_b and T_b
G_s	Gain Coefficient for steady flow
G_{us}	Gain Coefficient for unsteady flow

$$Q_{1,us} = 3.23\left(\frac{T_b}{p_b}\right)\sqrt{\frac{\left(P_i^2 - P_f^2\right)D^{\frac{16}{3}}}{\overline{Z}\overline{T}\gamma_g}\left(\frac{\Delta t}{0.032L\Delta t + 0.0000157D^{\frac{4}{3}}\Delta t + 0.083D^{\frac{4}{3}}L}\right)} \tag{2}$$

equation. Also, Zhou and Adewumi (1998) obtained a steady-state gas flow equation without neglecting any term in the momentum equation. Osiadacz and Chaczykowski (2001) compared isothermal and non-isothermal pipeline gas flow in the unsteady conditions. Chaczykowski (2009, 2010) investigated the effect of thermal model for analyzing unsteady gas pipelines. 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. Also, an analytical approach for simulating a pipeline networks under unsteady conditions presented by Farzaneh-Gord and Rahbari (2016). They considered a one dimensional isothermal compressible viscous flow with kirchhoff's lows.

However, steady flow in pipeline operation seldom exists in actual practice due to variation in input and output gas volume. In fact, deviation from steady flow is a major cause of error in the calculation of gas flow rate in a pipe. Although, there are some reports about unsteady flow in a single gas pipeline, but, there is no report about calculation of gas flow for pipeline networks under unsteady condition. Therefore, this paper attempts to fill this gap for gas networks in series, parallel and looped pipelines. The results of this paper are useful for engineers to make more accurate flow capacity forecasts in natural gas networks.

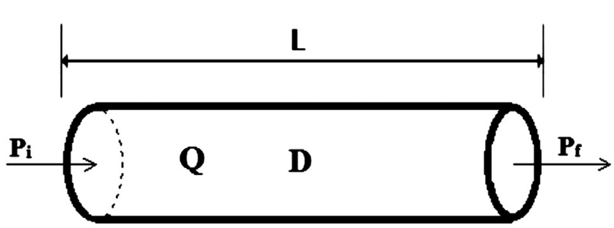

Fig. 1. A sketch of a single pipeline.

2. Fundamental gas flow equations for a single horizontal pipeline

Fig. 1 represents a schematic of a single horizontal pipeline which transports natural gas to market. For steady flow, Weymouth equation is the most fundamental equation and is expressed as (Adeosun et al., 2009):

$$Q_{1,s} = \frac{18.062T_b}{p_b}\sqrt{\frac{p_i^2 - p_f^2}{\gamma_g\overline{T}\overline{z}\left(\frac{L}{D^{\frac{16}{3}}}\right)}} \tag{1}$$

where T_b is base temperature, p_b is base pressure and $Q_{1,s}$ is steady volumetric gas flow rate in the pipeline. According to Adeosun et al. (2009), the unsteady flow in the pipeline ($Q_{1,us}$) with a given pressure drop can be described by the following equation.

3. Fundamental gas flow equations for horizontal pipeline networks

Optimization of pipelines mainly focuses on de-bottlenecking of the pipeline network, that is, finding the most restrictive segments and replacing/adding some segments to remove the restriction effect. This requires the knowledge of accurate gas flow in the pipe. As simulation can be useful for designers to optimize the pipeline networks, therefore, our work simulates gas volumetric flow rate for various gas pipeline networks under unsteady flow for real systems (Fig. 2). Also, a comparative study between steady and unsteady flow for pipelines in series, parallel and looped is carried out. The results of this work help the researchers to have a good prediction of gas flow rate under unsteady condition in the networks.

3.1. Pipeline network gain coefficient

First, we define pipeline network gain coefficient (G) as the ratio of gas flow rate in the pipeline network to gas flow rate in a single pipeline at the same pressure drop. Therefore, we have:

$$G = \frac{Q_N}{Q_1} \tag{3}$$

where G is gain coefficient of pipeline network. Also, Q_1 and Q_N are volumetric gas flow rate for a single pipeline and the pipeline network, respectively. However, choose of an appropriate value of G is very important for designers to achieve the maximum gas flow rate.