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# A steady state simulation method for natural gas pressure-relieving systems

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ABSTRACT

The natural gas pressure-relieving system is essential to natural gas pipelines and equipment for their safe operations against overpressure. This paper divided the system into pipe and resistance elements (valve, bent, tee et al.). The pipe elements are simulated by the hydrodynamic and thermodynamic equations, and the resistance elements are simulated by their characteristic equations. Combined those two kinds of equations, as well as the composition-dependent physical property models of natural gas, a steady-state simulation model of pressure-relieving systems is proposed for pressure, flow rate and temperature predictions. The homogeneous assumption is introduced to handle two-phase flow. A velocity constraint is also integrated into the model, making it applicable for both critical and subcritical pressure relief situations. Besides, the proposed solution method is applicable for any pressure-relieving systems composed of any numbers of pipe and resistance elements, as long as there are no branches. Finally, the reliability of the model has been examined using experimental data from three real pressure-relieving systems in Sichuan Province, China. The experiments cover a wide pressure range from 2.23 MPa to 53.80 MPa, and a temperature range from 257.40 K to 335.70 K. The results show that the maximum temperature and flow rate relative errors between the simulation results and experimental data are 1.03% and 3.52%, while the minimum values are 0.22% and 0.31%. The average absolute errors of the temperature and flow rate are 1.83 K and 1.00 $\times$ $10^4$ $m^3/d$. The method is also successfully applied to a gas well under critical and subcritical conditions.



## 1. Introduction

The natural gas pressure-relieving system is composed of the pressure relieving pipe, the choke valve, the vent valve and other equipment. It is used for the protection of all the equipment against overpressure situations (Mokhatab and Poe, 2006). Once there is an overpressure, the system should discharge sufficient gas in a short time to relief the pressure. Hence, the proper design of the system is important for the adequate discharge ability.

Generally, the mass, momentum and energy conservation laws are basic rules of flowing simulation in the pipe systems. Based on those three laws, many theoretical methods and associated commercial software packages have been developed for regular natural gas transmission pipelines with satisfactory accuracy (Alamian et al., 2012; Herrán-González et al., 2009). Contrary to the relative slow gas velocity in the regular pipelines, pressure-relieving systems often have much higher gas flow velocities. The inlet of the systems is trunk gas pipelines or gas processes equipment, and the outlet is atmosphere. The large pressure difference between the inlet and outlet can make the gas velocity even reach the local sonic velocity (Mahgerefteh and Wong, 1999). The flow condition of velocity equaling to local sonic velocity is called “critical flow state”, which means the local sonic velocity is the limited rate of gas reliving. However, the conservation laws mentioned above cannot express this velocity limit without specific constraints. In other words, if the critical state is not constrained by additional equations, the unreal supersonic gas velocity can be observed by using simulation methods for regular gas pipelines (Ye, 1995, 1999). On the other hand, the reliving caused pressure drop would lead great temperature drop because of the Joule-Thompson effect. The low temperature may further cause the gas condensation, two-phase flow in the pipe and brittle fracture of the pipe material. These features lead to different considerations in design of natural gas pressure-relieving systems compared to regular transmission pipelines.

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Nowadays, many empirical correlations and theoretical methods have been proposed to design pressure-relieving systems. One of the most simple and probably design methods is illustrated in the ANSI/API Standard 521 (Pressure-relieving and Depressuring systems) (API, 2007). API 521 chooses an isothermal flow equation based on inlet/outlet Mach number to determine the size of singe-phase gas pressure-relieving line. It also adopts a homogeneous equilibrium flow assumption to determine the pressure drop in two-phase horizontal pipelines. Both single-phase and two-phase calculation methods take into account the critical and subcritical flowing conditions. Recently, many scholars have researched more methods for the design of the pressure relief pipe system. Based on the prefect gas law, gas isentropic expansion, adiabatic assumptions and the gas pipe momentum equation, László et al. (László, 2001) developed a computational process for pressure, temperature and velocity predictions in the single-phase gas pipe blow-off systems. Kwang et al. (Won et al., 2006) researched the rigorous thermophysical property model of the natural gas that can be used in pressure-relieving systems. Raimondi (2007) proposed a rigorous method for the critical pressure and temperature calculation. But the friction pressure loss along the pipe is ignored. Pokki et al. (Pokki, 2001) and Luft (Luft et al., 2007) studied dynamic simulation methods for gas flows through the pressure relief valve.

Although many significant improvements have been achieved in recent years, there are still two aspects which need to be improved. The first aspect focuses on the rigorous thermodynamic modeling. Above methods have all adopt isothermal or adiabatic assumptions to simplify the model. These assumptions are reasonable for short pressure relieving pipes and choke valves. However, the real length of the pressure relieving pipe is often more than one hundred meters. The temperature change along the pipe and the heat transfer between the fluid and outer environment should not be neglected. The test data show that the temperatures of some high pressure systems may even drop to −46 °C. Consequently, the rigorous thermodynamic model for pipe should be integrated into the simulation model to improve the accuracy. The other aspect focuses on simulating the pipes, valves and other elements as an integrated system. Above methods provide some convenient and efficient methods for the single pipe and valve. However, the pressure-relieving system is a complicated and integrated system. The flow parameters, such as the flow rates, pressures and temperatures in each element, are interdependent and continuous (Dorao and Fernandino, 2011; Vasconcelos et al., 2013). Consequently, the models of all the elements should be solved simultaneously to improve the accuracy.

The purpose of the paper is to develop a rigorous theoretical model for pressure-relieving systems. The model integrates the hydrodynamic and thermodynamic models for the pipe and resistance element as well as the thermophysical properties of the natural gas. The model can be used for the system with any number of pipes and resistance elements in both the critical and subcritical pressure relief conditions.

## 2. Model establishment

### 2.1. The hydrodynamic model of pressure-relieving pipes

The hydrodynamic model is used to predict pressures and flow rates in the pressure-relieving pipes. It can be derived from the basic continuous and momentum equations for single-phase pipelines. The general continuous and momentum equations for single-phase pipe flow are as follows.

The continuous equation (Wylie et al., 1993):

$$A\frac{\partial\rho_m}{\partial t}+\frac{\partial}{\partial x}(\rho_m V_m A) = 0 \tag{1}$$

The momentum equation:

$$\frac{\partial G_v}{\partial t}+\frac{1}{A}\frac{\partial\left(G_v^2 A/\rho_m\right)}{\partial x} = -\frac{\partial P}{\partial x}-g\rho_m\sin\theta-\frac{\tau_w S}{A} \tag{2}$$

Generally, the steady state model is used in the design procedures. So, Eqs. (1) and (2) can be transformed into Eqs. (3) and (4) as follows.

Steady state continuous equation:

$$\frac{1}{\rho_m}\frac{d\rho_m}{dx}+\frac{1}{V_m}\frac{dV_m}{dx}+\frac{1}{A}\frac{dA}{dx} = 0 \tag{3}$$

Steady state momentum equation:

$$-\frac{dP}{dx} = \frac{\tau_w S}{A}+G_v\frac{dV_m}{dx}+g\rho_m\sin\theta \tag{4}$$

The wetted perimeter $S$ and shear force $\tau_w$ in Eqs. (2) and (4) are defined by Eqs. (5) and (6):

$$S = \frac{4A}{d} \tag{5}$$

$$\tau_w = \frac{\lambda}{8}\rho V_m^2 \tag{6}$$

If Reynolds Number is less than 2000 (Re < 2000), the fanning friction factor is calculated by Eq. (7).

$$\lambda = \frac{64}{Re}\quad (Re < 2000) \tag{7}$$

Otherwise, it should be calculated by the following Colebrook–White correlation (Mokhatab and Poe, 2012).

$$\frac{1}{\sqrt{\lambda}} = -2\lg\left(\frac{\varepsilon}{3.7d}+\frac{2.51}{Re\sqrt{\lambda}}\right)\quad (Re \geq 2000) \tag{8}$$

If the liquid condensation and deposition appear in the pipe, the assumption that the liquid and gas phases have the same pressures, temperatures and velocities at the same section of the pipe should be adopted to build the homogeneous two-phase flow model (Awad and Muzychka, 2008).

Based on the assumptions, the continuous equation for two-phase flow model is the same as Eq. (3). The main difference between the single-phase and two-phase flow is the properties of the mixture should be calculated by the volume or mass weighted method based on the liquid–vapor phase equilibrium results.

The first term in right hand of the Eq. (4) is the friction pressure drop gradient; the second term is the acceleration pressure drop gradient; the last term is the gravity pressure drop gradient. These terms can be expressed by Eq. (9)–(11) in the presence of the liquid condensation.

$$\frac{\tau_w S}{A} = \frac{\lambda}{2}\frac{G_v^2}{d}\left[\frac{1}{\rho_l}+\alpha\left(\frac{1}{\rho_g}-\frac{1}{\rho_l}\right)\right] \tag{9}$$

$$G_v\frac{dV_m}{dx} = G_v^2\left\{\frac{d}{dx}\left[\frac{1}{\rho_l}+\alpha\left(\frac{1}{\rho_g}-\frac{1}{\rho_l}\right)\right]-\left[\frac{1}{\rho_l}+\alpha\left(\frac{1}{\rho_g}-\frac{1}{\rho_l}\right)\right]\frac{1}{A}\frac{dA}{dx}\right\} \tag{10}$$