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# Fast method for the hydraulic simulation of natural gas pipeline networks based on the divide-and-conquer approach

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ABSTRACT

To apply an implicit method to simulate a natural gas pipeline network, all involved components should be solved in a coupled manner. Therefore, the computation burden and time sharply increase with the network size and complexity rise. To solve this problem, a fast method, which is the decoupled implicit method for efficient network simulation (DIMENS) based on the divide-and-conquer approach, is proposed. In this method, first, the hydraulic variables of all multi-pipeline interconnection nodes are solved; next, the pipeline network is divided into several independent pipelines, and the equations for all pipelines are solved. Compared with the Stoner Pipeline Simulator (SPS), which is a well-known commercial pipeline simulation software worldwide, the DIMENS method yields comparable calculation accuracy with 2.5 times the calculation speed of the SPS. The DIMENS method has strong adaptability to the simulation of the pipeline network, and the computing time in the test example depends linearly on the number of grid nodes or number of pipelines.

## 1. Introduction

Natural gas, which is one of the cleanest and most efficient existing mineral energy sources, is important for the optimization of energy structures in the 21st century (Huang, 2012). Generally, gas sources are located far from the consumers. Pipelines have become the main method to transport natural gas. For example, North Sea natural gas is transported from the continental shelf to processing terminals on the Norwegian mainland and fed into long export pipelines to continental Europe (Helgaker and Ytrehus, 2012). Through numerical simulations of the gas pipeline network, the conditions of gas flow in the pipeline can be rapidly and accurately predicted to provide important information to dispatch security and issue accident warnings.

The simulation of the gas pipeline networks is composed of two parts: hydraulic simulation, which aims to obtain the hydraulic variables such as the pressure and flow rate, and thermodynamic simulation, which aims to obtain the thermal variables such as the temperature and enthalpy. Because the hydraulic variables are vital to describe the natural gas flow in the pipeline, many researchers (Kiuchi, 1994; Wylie et al., 1974) only implemented the hydraulic simulation. For non-isothermal pipelines, the thermodynamic simulation is required. The decoupled strategy (Barley, 2012; Helgaker and Ytrehus, 2012; Modisette, 2002) can be used to decompose the simulation process into hydraulic simulation and thermodynamic simulation. In the decoupled strategy, first, the hydraulic simulation is implemented to obtain hydraulic variables such as the pressure and flow rate; then, the thermodynamic simulation is carried out based on the hydraulic variables. Because of the importance of the hydraulic system in the pipeline simulation, it is crucial to find efficient methods to accelerate the simulation process.

The hydraulic simulation of a gas pipeline network can be performed using several numerical methods: characteristic method (Ouchiha et al., 2012; Yow, 1971), explicit finite difference method (Chaczykowski, 2010; Osiadacz, 1984), implicit finite difference method (; Abbaspour and Chapman, 2008; Helgaker and Ytrehus, 2012; Wylie et al., 1971, 1974), semi-implicit finite volume method (Greyvenstein, 2002; Wang et al., 2011), equivalent circuit method (Ke and Ti, 2000; Tao and Ti, 1998), state space model method (Alamian et al., 2012; Reddy et al., 2006), intelligent algorithms (Dorao and Fernandino, 2011; Madoliat et al., 2016; Marjani and Baghmolai, 2016; Wu et al., 2014), other method (Behrooz and Boozarjomehry, 2015; Dukhovnaya and Adewumi, 2000; Farzaneh-Gord and Rahbari, 2016; Pambour et al., 2016; Woldeyohannes and Majid, 2011; Zhang, 2016). The implicit finite difference method is preferred by many researchers

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**Nomenclature**

| | |
|---|---|
| $d$ | pipe internal diameter, m |
| $g$ | gravitational acceleration, m/s$^2$ |
| $m$ | mass flowrate, kg/s |
| $p$ | pressure, Pa |
| $t$ | time, s |
| $u$ | the corresponding component of general variable $\mathbf{U}$ |
| $w$ | flow velocity, m/s |
| $x$ | spatial coordinate, m |
| $A$ | cross-sectional area, m$^2$ |
| $M$ | number of pipelines in the pipeline networks |
| $N$ | number of sections into which the pipelines are divided |
| $\mathbf{U}$ | general variable |
| $T$ | temperature, K |

*Greek symbols*

| | |
|---|---|
| $\alpha$, $\beta$ | fundamental set of solutions |
| $\gamma$ | particular solution |
| $\rho$ | density of gas, kg/m$^3$ |
| $\theta$ | inclination angle of the pipe, rad |
| $\lambda$ | friction coefficient |
| $\Delta x$ | mesh spatial size, m |
| $\Delta t$ | time step, s |

*Superscript*

| | |
|---|---|
| $n$ | time level index |
| $m$ | related to the parameters of mass flowrate |
| $p$ | related to the parameters of pressure |

*Subscript*

| | |
|---|---|
| $i$ | node number or pipeline number |
| $p$ | under the conditions of constant pressure |
| $in$ | flow in |
| $out$ | flow out |
| $T$ | under the conditions of constant temperature |

because the time steps are not restricted by the spatial steps. This method is particularly commonly used in the development of commercial software for the gas pipeline network. However, the computation burden is huge because the method requires the simultaneous computation of the discretized equations for all components in the propulsion of the time layer; thus, the computer must have a large memory and a fast operating rate. In addition, the coefficient matrix of this algebraic equation system is a large sparse irregular matrix, which is neither diagonally dominant nor symmetrical arranged. As a result, it is difficult to use efficient and simple methods such as the three-diagonal-matrix algorithm (TDMA) and conjugate gradient (CG). The computation of this huge algebraic equation requires the application of general methods such as the Gaussian elimination method and LU decomposing method. Therefore, a smooth numerical simulation is difficult when there are many discretized points in the network. Although the sparse matrix technique can accelerate the process of solving the coefficient matrix, it cannot guarantee faster computation under extreme conditions because of its complexity and numerous uncontrollable factors that affect the acceleration results. Considering the above problems, a new fast method for the hydraulic simulation of natural gas pipeline networks based on the divide-and-conquer approach is proposed, which is called the decoupled implicit method for efficient network simulation (DIMENS).

The outline of this paper is as follows: first, the mathematical model of the hydraulic simulation for natural gas pipeline networks and its discretization process are described; next, after detailed analyses of the divide-and-conquer approach, the implementation of the DIMENS method is elucidated; finally, the simulation accuracy and efficiency of the DIMENS method are validated by simulating the shutdown and restart process of a complex pipeline network.

## 2. Mathematical model for the hydraulic simulation of natural gas pipeline networks

For a brief and clear description of the DIMENS method, the pipeline network in this paper only includes pipelines. Therefore, the pipeline components are only considered in the mathematical mode.

### 2.1. Hydraulic governing equations of natural gas pipelines

The hydraulic governing equations of natural gas pipelines include the continuity equation and momentum equation (Chaczykowski, 2010; Helgaker and Ytrehus, 2012; Wang et al., 2011, 2015).

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho w)}{\partial x} = 0 \tag{1}$$

$$\frac{\partial(\rho w)}{\partial t} + \frac{\partial(\rho w w)}{\partial x} + \frac{\partial p}{\partial x} = -\frac{\lambda}{2}\frac{\rho w|w|}{d} - \rho g \sin\theta \tag{2}$$

where $\rho$ is the density, $w$ is the velocity, $p$ is the pressure, $\lambda$ is the friction, $d$ is the pipe internal diameter, $g$ is the gravitational acceleration, $\theta$ is the inclination angle of the pipe, $x$ is the spatial coordinate, and $t$ is time.

These equations can be transformed into Eq. (3), and the detailed transformation is described in (Wang et al., 2015).

$$\frac{\partial \mathbf{U}}{\partial t} + \mathbf{B}\cdot\frac{\partial \mathbf{U}}{\partial x} = \mathbf{F} \tag{3}$$

where $m$ is the mass flowrate; $A$ is the cross-sectional area; $T$ is the temperature; $\mathbf{U} = [p \quad m]^T$;

$$\mathbf{B} = \begin{bmatrix} 0 & \frac{1}{A}\left(\frac{\partial p}{\partial \rho}\right)_T \\ \left[A - \frac{m^2}{A\rho^2}\left(\frac{\partial \rho}{\partial p}\right)_T\right] & \frac{2m}{A\rho} \end{bmatrix}; \quad \mathbf{F} = \begin{bmatrix} \left(\frac{\partial p}{\partial T}\right)_\rho \frac{\partial T}{\partial t} \\ -\frac{\lambda}{2}\frac{m|m|}{dA\rho} - A\rho g \sin\theta + \frac{m^2}{A\rho^2}\left(\frac{\partial \rho}{\partial T}\right)_p \frac{\partial T}{\partial x} \end{bmatrix}$$

### 2.2. Boundary conditions

The boundary of a gas pipeline network can be classified into externals and multi-pipeline interconnection nodes. The externals are the supplies and demands, where gas can be injected into and extracted from the network, respectively. The multi-pipeline interconnection nodes are virtual components, where the pipelines are connected. For the externals, the pressure and flow rate are provided and called the external boundary conditions (Pambour et al., 2016) (Eqs. (4) and (5)). For each multi-pipeline interconnection node, the laws of mass conservation and pressure equality must be observed, which are called the internal boundary conditions (Zheng, 2012) (Eqs. (6) and (7)).

$$p = p(t) \tag{4}$$

$$m = m(t) \tag{5}$$

$$\sum m_{in} = \sum m_{out} \tag{6}$$