Determination of Gas Pressure Distribution in a Pipeline Network using the Broyden Method

Kuntjoro Adji Sidarto[1,3], Adhe Kania[1,3,*], Leksono Mucharam[2,3], Darmadi[3], & R. Arman Widhymarmanto[4]

[1]Industrial and Financial Mathematics Research Group, Department of Mathematics, Faculty of Mathematics and Natural Sciences, Institut Teknologi Bandung, Jalan Ganesha 10, Bandung 40132, Indonesia
[2]Drilling & Production Engineering and Management of Oil and Gas Research Group, Department of Petroleum Engineering, Faculty of Mining and Petroleum Engineering, Institut Teknologi Bandung, Jalan Ganesha 10, Bandung 40132, Indonesia
[3]Research Consortium OPPINET, Institut Teknologi Bandung, Jalan Ganesha 10, Bandung 40132, Indonesia
[4]Perusahaan Gas Negara (PGN), Jalan K.H. Zainul Arifin 20, Jakarta 11140, Indonesia
*E-mail: adhe.kania@math.itb.ac.id

Abstract. A potential problem in natural gas pipeline networks is bottlenecks occurring in the flow system due to unexpected high pressure at the pipeline network junctions resulting in inaccurate quantity and quality (pressure) at the end user outlets. The gas operator should be able to measure the pressure distribution in its network so the consumers can expect adequate gas quality and quantity obtained at their outlets. In this paper, a new approach to determine the gas pressure distribution in a pipeline network is proposed. A practical and user-friendly software application was developed. The network was modeled as a collection of node pressures and edge flows. The steady state gas flow equations Panhandle A, Panhandle B and Weymouth to represent flow in pipes of different sizes and a valve and regulator equation were considered. The obtained system consists of a set of nonlinear equations of node pressures and edge flowrates. Application in a network in the field involving a large number of outlets will result in a large system of nonlinear equations to be solved. In this study, the Broyden method was used for solving the system of equations. It showed satisfactory performance when implemented with field data.

Keywords: *Broyden method; gas pipeline network; pressure distribution; steady state gas flow.*

1 Introduction

Natural gas is widely used as a source of energy for industrial needs and public household consumption. Gas operators have the responsibility to provide gas to their consumers at a certain rate and pressure at their request. The gas operator should be able to preserve the gas pressure distribution and flowrate at each outlet or the consumer's entry point. There are two main problems in natural gas distribution networks: optimization of pipeline diameter and determination of

Received March 1st, 2017, 1st Revision May 10th, 2017, 2nd Revision November 11th, 2017, Accepted for publication December 14th, 2017.
 ISSN: 2337-5779, DOI: 10.5614/j.eng.technol.sci.2017.49.6.4

pressure distribution. Some research on pipeline diameter optimization can be found in [1-3], while some research on the determination of the pressure distribution in transmission networks can be found in [4], and more recently in [5].

The author in [5] expresses concern about the scarceness of methods for flow computation for gas networks in the presence of multiple pressure levels. This feature is important in the analysis of real gas systems, where most of the observed networks cannot be decomposed into pressure-homogeneous portions, so they will be solved independently. In the same paper, a steady-state flow formulation with multiple pressure levels is proposed and implemented into a gas distribution network containing 67 nodes and 88 edges. It also takes into account corrections for elevation changes in the pipes.

The present study focused on determining gas pressure distribution in pipeline networks that have multiple sources with multiple pressures. The network was considered as connected pipelines with steady-state gas flow from one or more supply points to one or more delivery points. Also, the flow in valves and regulators was represented by an equation. Hence we have a system of nonlinear equations with several variables that constitute the system model. The Newton and quasi-Newton methods, which are widely used to iteratively solve systems of nonlinear equations, have an advantage in their speed of convergence once they are given a sufficiently accurate initial guess of the root. Nowadays, the most commonly used approach is to run an optimization method first to find the desired initial guess and then feed it to the Newton method. This hybrid approach has been proven to be more satisfactory than using the root finding method solely. Luo, *et al.* [6] proposed a hybrid approach using a chaos optimization algorithm and the quasi-Newton method, while Burden and Faires [7] used a combination of the steepest descent method and the Newton method for solving the nonlinear equation system. The latest approach is given by Sidarto & Kania in [8]. Because solving nonlinear equation systems is related to the pressure distribution in gas pipeline distribution networks, Sidarto, *et al.* [9,10] have proposed a genetic algorithm optimization method combined with the Newton method. It uses the genetic algorithm to obtain a good initial guess of the root that is used by the Newton-type method to obtain the solution of the nonlinear equation system. However, for large systems it is observed that the convergence of the optimization process before applying the Newton-type method is rather slow. Detailed information on converting the root finding problem to an optimization process can be found in [8].

Using the Newton method for solving a system of n nonlinear equations with n variables, not only the function definitions must be provided but also the n^2 partial derivatives of the functions at each iteration. For large systems this is certainly a disadvantage of the method. The Broyden method avoids the calculation of those partial derivatives. In the present research, Broyden's method was used so matrix inversion does not need to be computed at each step [11]. The details will be explained in Section 4. Nowadays, this method is used in many applications. According to [12], the industrial practice of branched gas transmission network (GTN) analysis and operation requires high-accuracy computational fluid dynamics (CFD) simulators. The numerical solution of the obtained system of equations was performed by the modified Broyden method, which has been proven to be one of the best performing extensions of the classical secant method for numerical solution of non-linear algebraic equations. In [13], the development of strongly nonlinear problems in helicopter aeroelasticity is considered. For strongly nonlinear problems, numerical solutions obtained in an iterative process can diverge due to numerical instability. Therefore, choosing the method is critical. In the same research, a comparative study was conducted using the modified Newton, rank-1 Broyden, and rank-2 BFGS (Broyden-Fletcher-Goldfarb-Shanno) update methods. One of the results showed that Broyden's update method gives a reduction of the number of iterations relative to the Newton method and it gives a higher rate of convergence. The convergence of the Broyden method has been extensively studied in [14] and [15].

The obtained result of this new approach was compared to the result from TGNet, a commercial software application commonly used in natural gas pipeline network simulation. The software application is suitable for static pipeline network simulation [16]. According to [17], it gives better performance compared to other well-known software applications in single-phase gas flow simulation, such as OLGA and SPS. The new approach was developed as a new software application, called DistNet by OPPINET, in which the initial values are generated randomly and the calculation of solutions for the system of equations is conducted using the Broyden method. It will be shown that its performance is as good as that of TGNet, which validates the results of DistNet. This software application has some features that are not found in TGNet, such as providing a choice between meta-heuristic methods combined with the Newton or quasi-Newton method so its running time can be managed to give better performance.

2 Methodology

A complex gas pipeline network can be modeled as a directed and connected graph (V,E), in which $V=\{v_i \mid i=1,2,\ldots,N\}$ is the set of vertices/nodes consisting of inlets, outlets, and junctions $V=V_I \cup V_O \cup V_J$. E is the set of directed edge connecting nodes representing the flows' directions, so it consists of pipes, valves, and regulators. Each flowrate that connects node i and node j is governed by the steady empirical gas flow equation and also by the valve and regulator equation. The constraints used in the determination of the flowrate and pressure distribution are the balancing equations, which are based on Kirchhoff's law.

In solving the obtained system of equations, we use the Broyden numerical method, which is a quasi-Newton method for finding the roots of a system of N nonlinear equations for N variables. The Newton method for solving the system needs the computation of the Jacobian matrices at every iteration, which is a difficult and expensive operation for the system when N is quite large. The Broyden method computes the Jacobian matrix only once, at the first iteration, and does a rank-one update at the rest of other iterations.

3 Gas Flowrate Equations on Pipes and Valves/Regulators

A pipeline system consists of nodes and node-connecting elements (NCE). Nodes represent points where one or more NCEs terminate and where a gas flow enters or leaves the system. Nodes are also the reference points for the pressures of the system. Several types of NCE commonly used in networks are pipelines, compressors, valves, and regulators. In this study, all these types were considered, with the exception of compressors. In balancing the flowrates using a mathematical model, a steady-state model from the continuity equation at each node in the system was used [18]. The Weymouth, Panhandle A and Panhandle B gas flow equations were used to represent flow in different sizes of pipes. The most common pipeline flow equation is the Weymouth equation, which is generally preferred for transmission line diameters smaller than 15 inch. The other equations are usually better for larger-sized transmission lines. These equations were developed to simulate compressible gas flows in long pipelines [19]. A pipe that connects node i and node j has length L_{ij} (mile), with inside diameter ID_{ij} (inch), average flowing temperature T_{ij} (°F), specific gravity G_{ij} and pipe efficiency E_{ij}. The pipeline system in this research was assumed to be in steady-state condition. The flow from node i to j is expressed as a flow with a positive signed value. The gas flowrate is expressed in units of MMSCFD (million standard cubic feet of gas per day) and the gas pressure is expressed in units of psia (pounds per square inch absolute).

For horizontal flow, the general flowrate equation in a pipeline is written as follows [19]:

$$Q_{ij} = a_1 \, E_{ij} \left(\frac{T_b}{P_b} \right)^{a_2} \left(\frac{P_i^2 - P_j^2}{T_{ij} \, z \, L_{ij}} \right)^{a_3} \left(\frac{1}{G_{ij}} \right)^{a_4} ID_{ij}^{a_5} \tag{1}$$

where Q_{ij} is the volumetric gas flowrate in a pipe that connects nodes i and j. P_i and P_j are the pressures at nodes i and j respectively. T_b and P_b are the base temperature and pressure respectively. z is the gas deviation factor at average flowing temperature and average pressure. The different values of $a_i, i = 1,...,5$ represent parameters for different flow equations, which are given in Table 1.

Table 1 Parameter values for the different pipeline flow equations.

Equation	a_1	a_2	a_3	a_4	a_5
Panhandle A	435.87	1.0788	0.5394	0.4604	2.618
Panhandle B	737.0	1.02	0.510	0.490	2.530
Weymouth	433.5	1.0	0.5	0.5	2.667

Valves and regulators have different functions: valves manage the flowrate and regulators manage the flow pressure. However, the flowrate equations for both valves and regulators are the same:

$$Q_{ij} = C_{ij} \sqrt{\frac{P_i^2 - P_j^2}{2 \, G_{ij} \, T_{ij}}} \tag{2}$$

where Q_{ij} and C_{ij} are respectively the volumetric gas flowrate and the coefficient of a valve/regulator that connects nodes i and j. Here P_i and P_j are the upstream and downstream pressures of a valve/regulator respectively. In the valve model, the value of coefficient C_{ij} is given, but the values of the upstream and downstream pressures, P_i and P_j, are estimated. In the regulator model, the value of downstream pressure P_j is given, but the values of coefficient C_{ij} and upstream pressure P_i are estimated.

The gas flow balancing method was developed based on Kirchhoff's law about the conservation of electric charge. In the gas distribution system its analogue that the algebraic summation of the gas flowrates entering and leaving all nodes is zero was used. Let f_m be the total flowrate at a node m, and N the total number of nodes in the system. The continuity equation is in the following form:

$$f_m = \sum_{k=1}^{n_m} Q_{km} + QN_m = 0 \quad , \quad m = 1,2,\ldots,N \tag{3}$$

Here n_m is the total number of all nodes adjacent to node m, while k, for $k=1,...,n_m$, are the indices of all nodes adjacent to node m. The flowrate, Q_{km}, is determined by Eq. (1) or (2), and its direction is indicated with a plus or minus sign. Here, QN_m is the flowrate into or out of the system at node m. Herein f_m is a nonlinear equation at nodes m and it represents the flow imbalance at some points. Therefore, $f_m = 0$ for $m = 1,2,\ldots,N$ if the system is in a state of balance.

Having two variables at each node, pressure p and in/out flow QN, and a variable of each NCE, there will be a total of $2N + M$ variables, where N is the number of nodes and M is the number of NCEs. Provided only N nodal equations are developed in the system of Eq. (3), N variables are to be unknown state variables and $N + M$ variables are to be decision variables with given fixed values so that the system of equations can be solved. The state variables consist of $N - 2$ pressure variables, one QN variable and one coefficient variable of a regulator. Having a large number of N nodes in a pipeline network there will be N nonlinear equations to solve, so a large number of computations is needed as well as good convergence behavior.

4 Broyden Numerical Methods

The Broyden method is for numerically solving a nonlinear system of equations and is derived from the Newton method [7]. Consider a system of nonlinear equations $\vec{F}(\vec{x}) = \vec{0}$ and a given initial approximate solution $\vec{p}_0$. The method generates a sequence $\{\vec{p}_k\}$ that will converge to $\vec{p}$ such that $\vec{F}(\vec{p}) = \vec{0}$. For the Newton method and $k \geq 0$, first compute $\vec{F}(\vec{p}_k)$ and the Jacobian matrix $J(\vec{p}_k)$, then find $\Delta\vec{p}$ that satisfies

$$J(\vec{p}_k)\, \Delta\vec{p} = -\vec{F}(\vec{p}_k)$$

So we have the following iteration formula:

$$\vec{p}_{k+1} = \vec{p}_k + \Delta\vec{p} \tag{4}$$

The Broyden method replaces the computationally expensive Jacobian matrix $J(\vec{p}_k)$ with a simple choice matrix A_k. Initially the method sets $A_0 = J(\vec{p}_0)$. For the computation of matrices A_k $k > 0$ as the next replacement of the Jacobian matrices the following update is used:

$$A_k = A_{k-1} + \frac{1}{\vec{S}_k{}^T \vec{S}_k} \left(\vec{Y}_k - A_{k-1} \vec{S}_k \right) \vec{S}_k{}^T$$

where $\vec{S}_k = \vec{p}_k - \vec{p}_{k-1}$ and $\vec{Y}_k = \vec{F}(\vec{p}_k) - \vec{F}(\vec{p}_{k-1})$,

So we find $\Delta\vec{p}$ that satisfies:

$$A_k \, \Delta\vec{p} = -\vec{F}(\vec{p}_k),$$

and the method from Eq. (4) gives:

$$\vec{p}_{k+1} = \vec{p}_k - A_k^{-1} \vec{F}(\vec{p}_k).$$

Furthermore, the Sherman-Morison matrix inversion formula (see for example [7]) is used to compute A_k^{-1} from A_{k-1}^{-1} by the following formula:

$$A_k^{-1} = A_{k-1}^{-1} + \frac{1}{\vec{S}_k{}^T A_{k-1}^{-1} \vec{Y}_k} \left(\vec{S}_k - A_{k-1}^{-1} \vec{Y}_k \right) \vec{S}_k{}^T A_{k-1}^{-1} \, ,$$

eliminating the need of a matrix inversion at each iteration.

5 Implementation on Field Application

The process of developing the model and the implementation of data are discussed in this section. Figure 1 shows the steps of implementing the process. The network scheme describes the flows within each couple index of pipelines and nodes. For each pipe its length and inside diameter are provided. The gas flowrate demand is specified at each outlet node. Related to the valves are data of the percentage of opening and the size. For the regulators, the required information consists of size, type and desired pressure.

The input data in Figure 2 were obtained from a large and complex network in XYZ, a quite large area in Indonesia. In the model it contains 91 nodes consisting of 1 inlet/source, 42 outlets, and 48 junctions. The inlet at node 1 is in the upper right of the figure. The outlets are in bullet form, called sinks, with numbers from 13-134. The junctions are indicated by diamonds. It also contains 91 pipelines, consisting of 79 pipes, 10 valves, and 2 regulators.

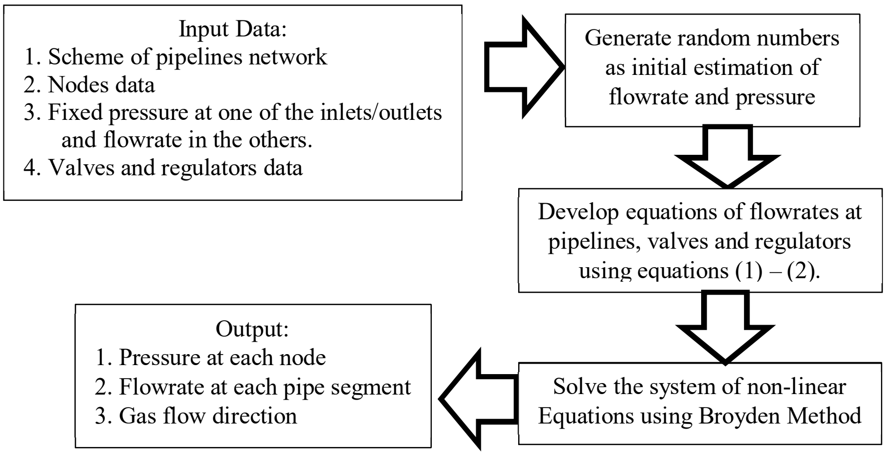

Figure 1 Steps of implementing the network simulation.

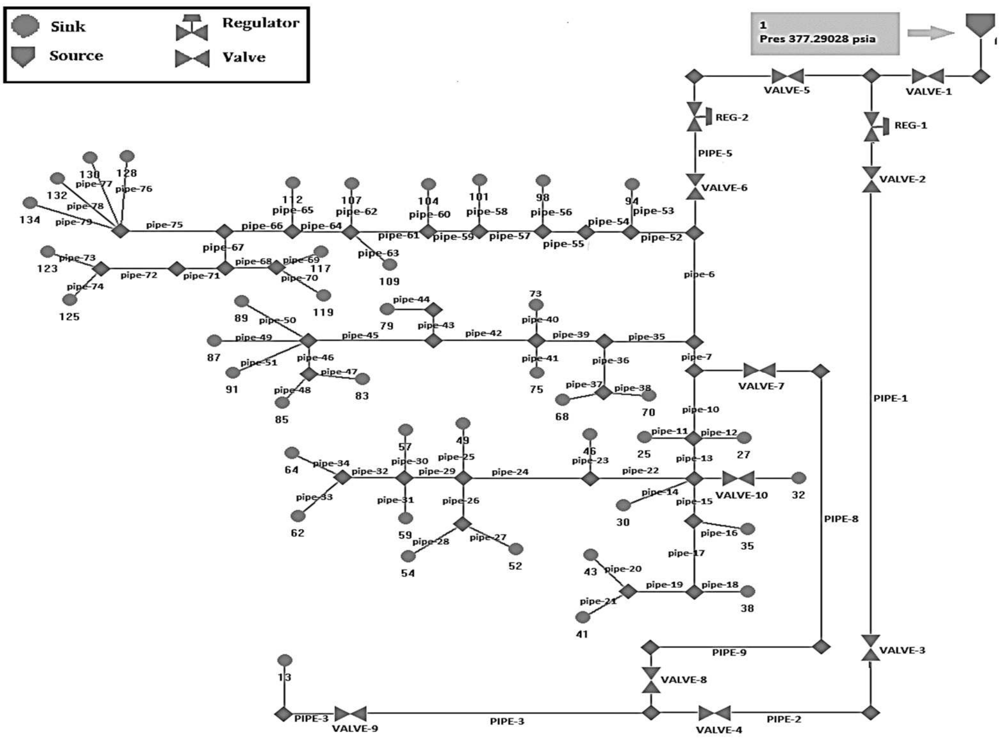

Figure 2 Scheme of the gas distribution pipeline network.

The pressure at the inlet/source node is 377.29 psia, and the temperature is 77 °F or 536.67 °R. The gas specific gravity that comes into the network through the inlet is 0.633729. There are 42 demand/outlet nodes in the network. The non-zero flowrate for each demand node is given in Table 2. Note that two demands are relatively large compared to the others, i.e. at outlets 13 and 128. The valve coefficient needed in Eq. (2) is $C_{ij} = 50{,}000 \cdot p \cdot s$, where p is the opening percentage and s is the size of the valve/regulator. The data of the main pipes are given in Table 3. 'Short' pipes that connect each outlet node to the corresponding main pipe have a length of 5 m and an inside diameter of 6 inch. The valve and regulator data are given in Tables 4 and 5. Thus there are 91 nodes, which gives a system of 91 non-linear equations. The system has 91 state variables, which consist of 89 node pressures, one flowrate at node-1 and one regulator coefficient (regulator-2).

Table 2 All non-zero demands in outlets (MMSCFD).

Outlet	Flowrate	Outlet	Flowrate	Outlet	Flowrate
13	39.5675	54	1.0613	98	0.1789
27	0.4047	57	5.2710	104	0.4242
30	0.0028	68	0.4023	107	0.0664
35	0.0069	73	3.7774	112	6.1654
38	0.0131	79	0.0495	119	1.5260
43	0.03602	85	0.9624	123	0.0706
46	0.2139	91	0.2050	128	32.061
49	2.1293	94	0.0105	132	0.1240

Table 3 Main pipe data.

Pipe	From node	To node	Length (m)	Inside diameter (in.)
Pipe-1	5	6	11550	19.5
Pipe-2	7	8	10.169	12.42
Pipe-3	9	10	2320.43	19.5
Pipe-4	11	12	2418.39	19.5
Pipe-5	15	16	1370	23
Pipe-6	17	18	7600	15.062
Pipe-7	18	19	505	15.062
Pipe-8	20	21	700	15.5
Pipe-9	21	22	150	19.5
Pipe-10	19	23	595	15.062
Pipe-13	23	28	800	15.062
Pipe-15	28	33	65	7.625
Pipe-17	33	36	535	7.625
Pipe-19	36	39	55	7.625
Pipe-22	28	44	830	15.062
Pipe-24	44	47	8800	15.062

Table 3 *Continued*. Main pipe data.

Pipe	From node	To node	Length (m)	Inside diameter (in.)
Pipe-26	47	50	455	3.876
Pipe-29	47	55	600	15.062
Pipe-32	55	60	1535	15.062
Pipe-35	18	65	3600	15.062
Pipe-36	65	66	1050	7.625
Pipe-39	65	71	560	15.062
Pipe-42	71	76	850	15.062
Pipe-43	76	77	500	5.875
Pipe-44	77	78	455	3.876
Pipe-45	76	80	170	15.062
Pipe-46	80	81	1050	7.625
Pipe-52	17	92	303	15.062
Pipe-54	92	95	9355	15.062
Pipe-55	95	96	4295	15.062
Pipe-57	96	99	500	15.062
Pipe-59	99	102	590	15.062
Pipe-61	102	105	800	15.062
Pipe-64	105	110	362	15.062
Pipe-66	110	113	200	15.062
Pipe-67	113	114	5	7.625
Pipe-68	114	115	10	5.875
Pipe-71	114	120	170	5.875
Pipe-72	120	121	830	7.625
Pipe-75	113	126	250	15.062

Table 4 Valve data.

Valve	Upstream Node	Downstream Node	% opening	Size (in.)
Valve-1	2	3	100	20
Valve-2	4	5	100	20
Valve-3	7	6	100	16
Valve-4	9	8	100	20
Valve-5	3	14	100	20
Valve-6	16	17	100	23
Valve-7	19	20	100	16
Valve-8	22	9	0	20
Valve-9	11	10	100	20
Valve-10	31	28	100	16

Table 5 Regulator data.

Regulator	Upstream node	Downstream node	Size (in.)	Mode	Downstream pressure (psia)
Reg-1	3	4	16	Bypass (free-flowing)	-
Reg-2	14	15	16	Max down Pressure	217.31633

Although the measures of the pipelines are not of the same type, the software application will consider them to be of the same type as chosen by the user. For example, if the user chooses Panhandle A, then all pipes are considered to be of the type Panhandle A. The software application cannot automatically choose the implemented equation based on the measurements of the pipes. This also occurs in TGNet software and other commonly used software applications. In our observation, the results in this paper do not give significant differences between the Panhandle A, Panhandle B and Weymouth correlations.

5.1 Examples on Developing the Equations

Now we give examples of developing the equations at node-15, node-17 and node-92 (see Figure 3). Detailed information about the pipes and the valve can be found in Table 6. Note that the values of $a_i, i = 1, \ldots, 5$, depending on the choice of Eq. (1) used, can be found in Table 1.

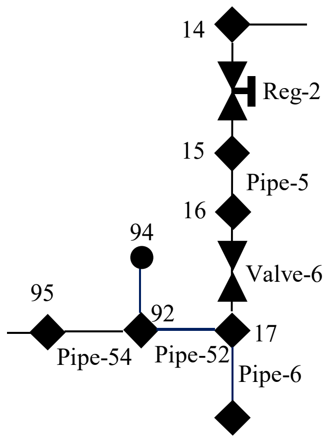

Figure 3 Example of developing equations at node-15, node-17 and node-92.

The equation of flowrate at regulator-2: $Q_{14,15} = C_{14,15}\sqrt{\frac{P_{14}^2 - 217.3163}{2 \cdot 0.6337 \cdot 536.67}}$.

The equation of flowrate at pipe-5:

$$Q_{15,16} = a_1 \cdot 0.9\left(\frac{520}{14.7}\right)^{a_2}\left(\frac{P_{15}^2 - P_{16}^2}{536.67 \cdot 0.969 \cdot 0.8513}\right)^{a_3}\left(\frac{1}{0.6337}\right)^{a_4} 23^{a_5}.$$

So the flowrate equation at node-15 is $Q_{14,15} - Q_{15,16} = 0$. The equation at node-15 has 4 unknown variables: P_{14}, P_{15}, P_{16} and $C_{14,15}$.

The equation of flowrate at valve-6: $Q_{16,17} = 50{,}000 \cdot 23\sqrt{\frac{P_{16}^2 - P_{17}^2}{2 \cdot 0.63373 \cdot 536.67}}$.

The equation of flowrate at pipe-6:

$$Q_{17,18} = a_1 \cdot 0.9\left(\frac{520}{14.7}\right)^{a_2}\left(\frac{P_{17}^2 - P_{18}^2}{536.67 \cdot 0.969 \cdot 0.1883}\right)^{a_3}\left(\frac{1}{4.7224}\right)^{a_4} 15.062^{a_5}$$

The equation of flowrate at pipe-52:

$$Q_{17,92} = a_1 \cdot 0.9\left(\frac{520}{14.7}\right)^{a_2}\left(\frac{P_{17}^2 - P_{92}^2}{536.67 \cdot 0.969 \cdot 0.1883}\right)^{a_3}\left(\frac{1}{0.6337}\right)^{a_4} 15.062^{a_5}$$

So the flowrate equation at node-17 is $Q_{16,17} - Q_{17,18} - Q_{17,92} = 0$. The equation at node-17 has 4 unknown variables: P_{16}, P_{17}, P_{18} and P_{92}.

Table 6 Information about pipes and valve.

Pipe	Connecting nodes	Length (m/mi)	ID (in.)
Pipe-5	15, 16	1370/0.8513	23
Pipe-6	17, 18	7600/4.7224	15.062
Pipe-52	17, 92	303/0.1883	15.062
Pipe-54	92, 95	9355/5.8129	15.062
Valve	**Connecting nodes**	**% opening**	**Size (in.)**
Valv-6	16, 17	100	23
Regulator	**Connecting nodes**	**Size (in.)**	**Downstream Pressure (psia)**
Reg-2	14, 15	16	217.31633

The equation of flowrate at pipe-54:

$$Q_{92,95} = a_1 \cdot 0.9\left(\frac{520}{14.7}\right)^{a_2}\left(\frac{P_{92}^2 - P_{95}^2}{536.67 \cdot 0.969 \cdot 5.8129}\right)^{a_3}\left(\frac{1}{0.6337}\right)^{a_4} 15.062^{a_5}.$$

Having demand 0.0104178 MMSCFD at outlet 94, the flowrate equation at node-92 is $Q_{17,92} - Q_{92,95} - 0.0104178 = 0$. It is clear that the equation at node-92 has 3 unknown variables: P_{17}, P_{92} and P_{95}.

5.2 Numerical Results

The software application was made using C++ and compiled using g++ on operating system Ubuntu 12.04 using a notebook with an Intel® Core™ i5 processor and 3.6 GB of memory. Figure 4 shows the result using the Panhandle A correlation. DistNet needed about 0.75 s. Comparing the result to TGNet in order to validate the results, if we calculate the difference with $\left|\frac{DistNet-TGNet}{DistNet}\right| \cdot 100\%$, the averages of the difference values for Panhandle A, Panhandle B and Weymouth are 0.0818%, 0.6818% and 1.8655% respectively.

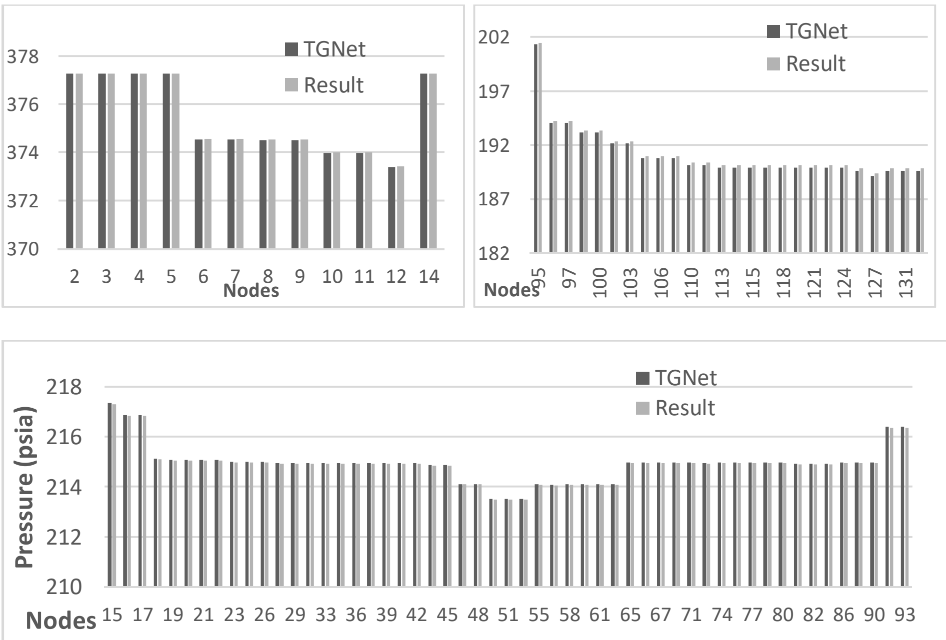

Figure 4 Results of Panhandle A using DistNet and TGNet: nodes 1-14 (upper left), 15-93 (lower), 95-132 (upper right).

The gas flow from inlet 1 is diverted into 2 paths: the path from node-4 to node-10 for supplying outlet-13, which has the largest flowrate demand, and the other path is from nodes 14, 15 and so on. It can be seen from Figure 4 upper left that nodes 2 to 14 have higher pressure values (around 372-378 psia). At nodes 15-94, the pressures decrease such that they are not higher than 218 psia. The pressures decrease again from node-95 onwards such that they are not higher than 200 psia. There is also a decrease from node-14 to node-15 due to an existing regulator-2 for which the downstream flow was set at 217.3163 psia. See Figure 3 for a detailed scheme.

The other significant decrease starts from node 95. This may be caused by the length of pipe-54 (9355 m). This length is the second longest after pipe-1 (11,550 m). This shows that the gas flow direction is from higher to lower pressures and that the demands at all outlets will be well fulfilled. This phenomenon also occurs in the models using Panhandle B and Weymouth equations.

In the actual field data from Table 4, valve-8 is closed, causing no looping flow in the network. Now we give the result in the case when valve-8 is open. The difference in pressure distribution is presented in Figure 5.

The gas flow from valve-8 shows a decrease or increase of pressure at particular nodes. A decrease of about 55 psia occurs at nodes 5 to 11 due to the diversion at valve-8. On the other hand, quite a large increase (about 90 psia) occurs at nodes 16 to 63. However, the pressure at nodes 64 to 91 goes down to the same pressure as in the original condition. Notice that these nodes are outlets of the system, which have a certain demand. This result shows that the method can distribute the pressure to fulfill the demands in both conditions of valve-8.

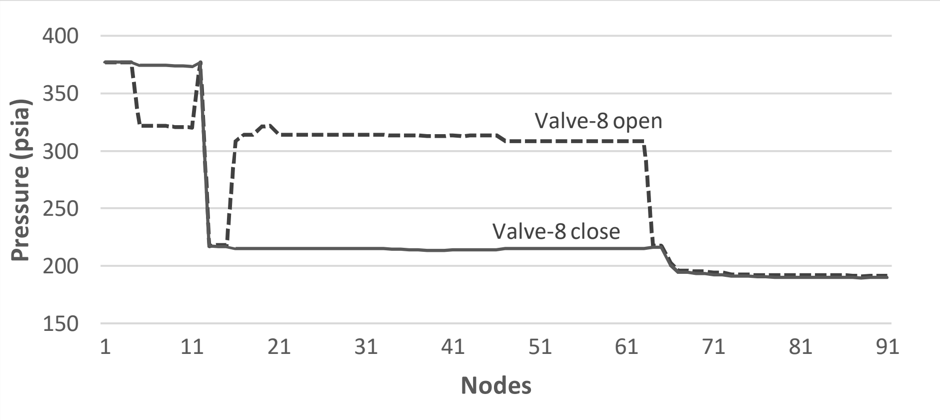

Figure 5 Difference of pressure distribution in the cases of valve-8 open and valve-8 closed.

In Figure 6, the temperatures are varied in order to see its impact on the pressure distribution in the system. It can be seen that the pressures distribution at each temperature (0, 20, 25, 35, and 50 °C) does not differs significantly.

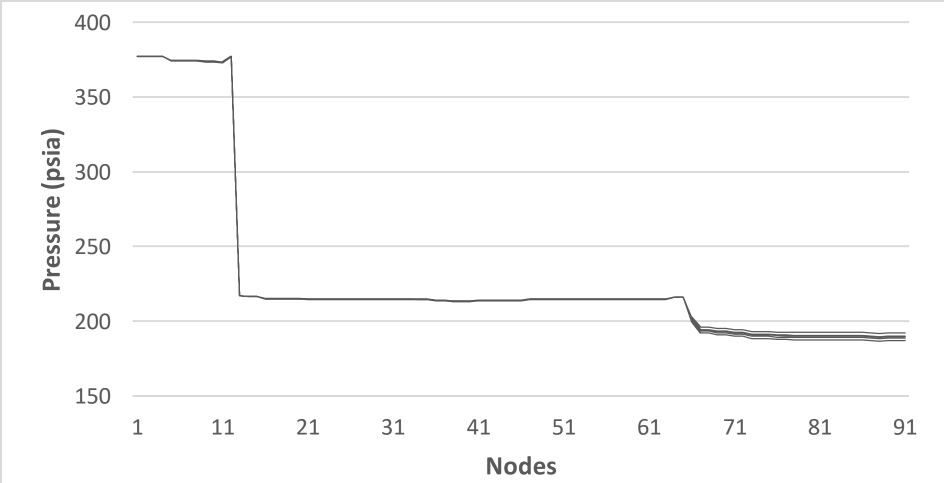

Figure 6 Difference of pressure distribution with T = 0, 20, 25, 35, 50 °C from bottom to top respectively.

5.2.1 Simplified Network

Now let us consider the network in Figure 2 without incorporating valves and regulators. The total number of observed nodes is 79. In Figure 7 and 8, the numbering of nodes is different from Figure 2 but the order is the same. The given data on node demands and pipeline sizes are the same.

First, we conduct a simulation in order to investigate the effect of the chosen value of source pressure on the gas supply for this simplified network. This is to find the minimum pressure at the source (inlet) node-1 in the network, where its original value is 377.29 psia. Remember that the gas supply has an expected minimum pressure of 50 psia at each node in the network. The results of these simulations are presented in Figure 7. The source pressure 377.29 psia at node-1 gives pressures values close to 377 psia at all other nodes. It can be concluded that the source pressure is too high for the current gas demand. When the source pressure (or Pi in Figure 7) is decreased to 300, 250, 200, 150 and 120 respectively, in order to see whether all nodes can reach a pressure value of at least 50 psia or not. Having source pressure 110 psia, the network system cannot supply gas at the minimum pressure for node-55 onward. Therefore it is concluded that the source pressure at node-1 can be as low as 120 psia for this modified network.

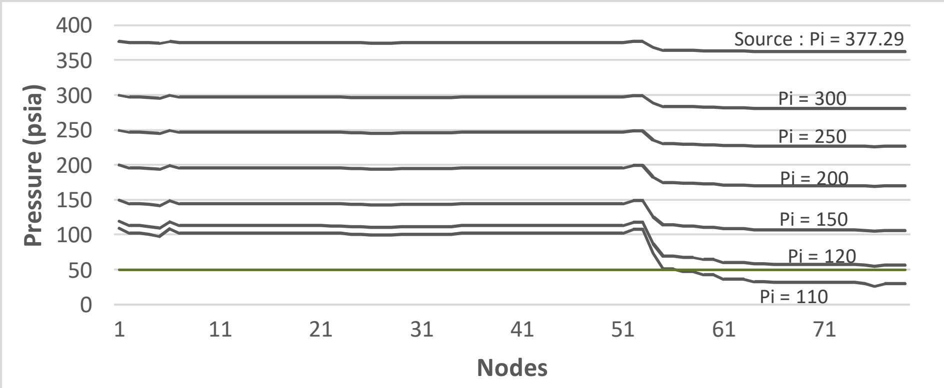

Figure 7 Effect of source pressure on the nodal pressure for the modified network.

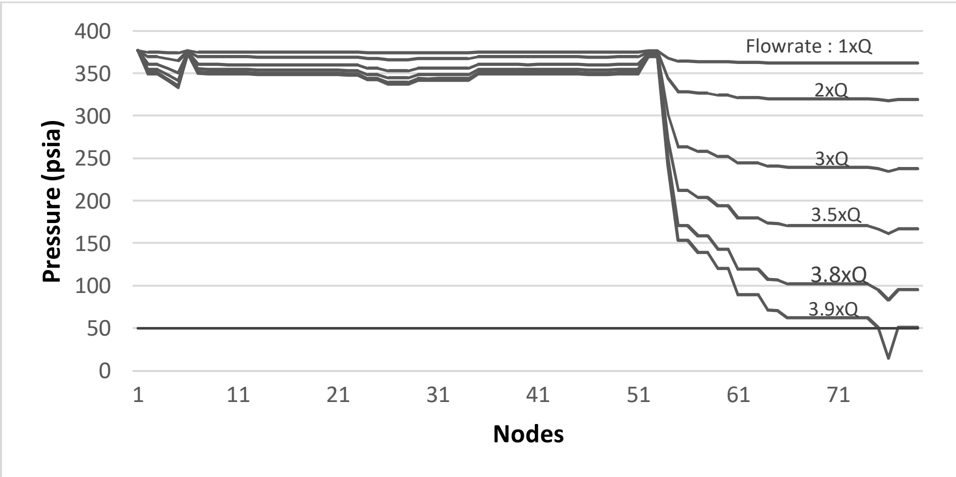

Figure 8 Flowrate simulation with source pressure at 377.29 psia.

In the next simulation, the flowrate demands at all outlets as listed in Table 2 (represented by Q in Figures 8-10) are increased by a multiplication factor. The largest factor that can be obtained in the simplified network system was sought. Using a certain value of source pressure at node-1 and these new flowrate demands it is also expected that all nodes have a pressure of at least 50 psia. Having an original pressure of 377.29 psia in Figure 8, the modified network system can support a flowrate demand that is up to 3.8 times greater than the original flowrate demand. If the source pressure is 200 psia (Figure 9) and 150 psia (Figure 10), the largest factors are 1.9 and 1.35 respectively.

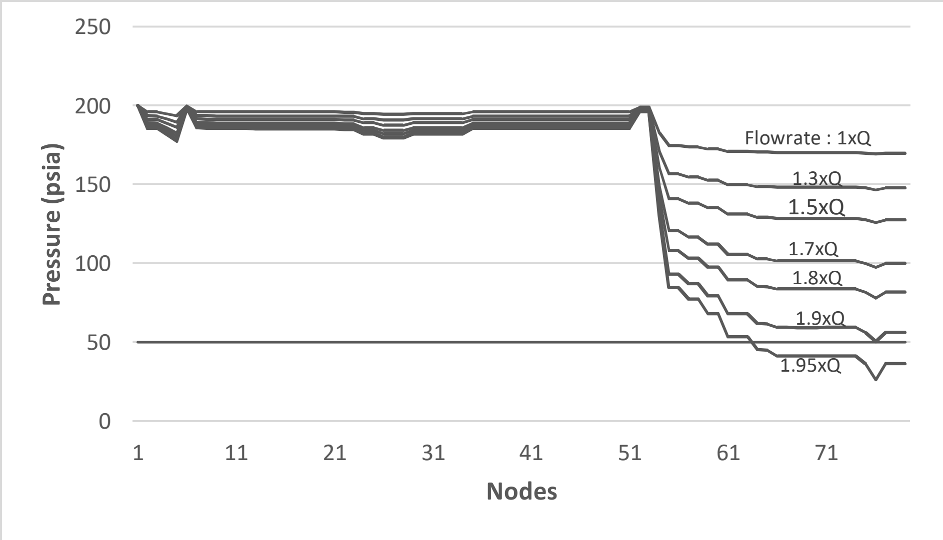

Figure 9 Flowrate simulation with source pressure at 200 psia.

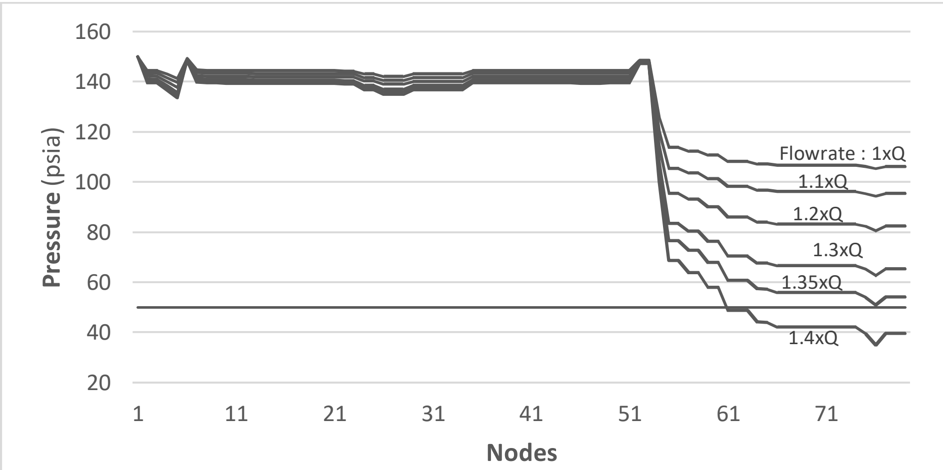

Figure 10 Flowrate simulation with source pressure at 150 psia.

6 Conclusion

The method developed in the novel software application DistNet was shown to have the ability to simulate a natural gas distribution network with pipes, valves, and regulators. By using the Broyden method, the pressure distribution and flow direction can be obtained within a short period of simulation time.

Note that the direction of the flow does not have to be defined in the input data because the model can determine the direction naturally as gas flow will go from higher pressure to lower pressure. If we have very high demand at one outlet, for example outlet-13 in the observed network, the pressures will be high along all nodes leading to that outlet.

The results of the DistNet software application are very close to those of TGNet. The average differences in pressure distribution for Panhandle A, Panhandle B and Weymouth Correlations are 0.082% 0.6818%, and 1.8655% respectively.

A simplified network without valves and regulators can be more efficient than the original network. In order to fulfil the same flowrate demands at all outlets, the source pressure can be reduced up to 30% of the original value. On the other hand, the simplified system with original source pressure can supply up to 3.8 times the original demand. Comparing the simulation results of the original and the simplified network, the existing valves and regulators installed in the original network seem to create inefficiency. However, conditions in the field sometimes create unexpected constraints, so the valves and regulators are still needed to control the pressures and flowrates.

Acknowledgments

The authors are grateful to the anonymous referees for their comments and suggestions, which have helped to improve this paper. Particular thanks are due to Novriana Sumarti for her generous help in the process of editing this paper.

References

[1] Flanigan, O., *Constrained Derivatives in Natural Gas Pipeline System Optimization*, Journal of Petroleum Technology, **24**(5), pp. 549-556, May 1972.

[2] Sung, W., Lee, J., Huh, D. & Kwon, O., *Optimization of Pipeline Network in Metropolitan Area, Korea, with Hybrid MCST-CD Networking Model*, Paper SPE 38101 presented at the SPE Asia Pacific Oil and Gas Conference, Kuala Lumpur, Malaysia, pp. 629-635, April 14-16, 1997.

[3] Wu, Y., Lai, K.K. & Liu, Y., *Deterministic Global Optimization Approach to Steady State Distribution Gas Pipeline Networks*, Springer Science+Business Media, **8**(3), pp. 259-275, 2007.

[4] Woldeyohannes, A.D. & Majid, M.A.A., *Simulation Model for Natural Gas Transmission Pipeline Network System*, Simulation Modelling Practice and Theory, **19**(1), pp. 196-212, 2011.

[5] Cavalieri, F., *Steady-state flow Computation in Gas Distribution Networks with Multiple Pressure Levels*, Energy, **121**(C), pp. 781-791, 2017.

[6] Luo, Y.Z., Tang, G.J. & Zhou, L.N., *Hybrid Approach for Solving Systems of Nonlinear Equations Using Chaos Optimization and Quasi-Newton Method*, Applied Soft Computing, **8**(2), pp. 1068-1073, 2008.

[7] Burden, R.L. & Faires, J.D., *Numerical Analysis*, 9th ed., Brooks/Cole, Boston, 2010.

[8] Sidarto, K.A. & Kania, A., *Finding all solutions of Systems of Nonlinear Equations Using Spiral Dynamics Inspired Optimization with Clustering*, J. of Advanced Computational Intelligence and Intelligent Informatics (JACIII), **19** (5), pp. 697-707, 2015.

[9] Sidarto, K. A., Mucharam, L., Saiman, Mubassiran, Rohani, N., Riza, L.S., Priambudi, A. & Nafis, P.A., *On the Steady-State Gas Distribution Pipeline Network Solution Using Genetic Algorithm*, Proc. of the 2nd Int. Conf. on Artificial Intelligence in Engineering & Technology, Sabah, Malaysia, pp. 944-949, August 3-5, 2004.

[10] Sidarto, K. A., Mucharam, L., Riza, L.S., Mubassiran, Rohani, N. & Sopian, S., *Implementation of Genetic Algorithm to Improve Convergent of Newton Method in Predicting Pressure Distribution in a Complex Gas Pipeline Network System*. *Case Study: Off-take Station ST-WLHR Indonesia*, Proc. of National Seminar SIIT, Surabaya, Indonesia, 2005.

[11] Broyden, C. G., *A Class of Methods for Solving Nonlinear Simultaneous Equations*, Math. of Comp. (AMS) **19** (92), pp. 577-593, 1965.

[12] Seleznev, V., *Computational Fluid Dynamics Methods for Gas Pipeline System Control*, Comp. Fluid Dyn., Chapter 15, INTECH, Croatia, 2010. http://www.intechopen.com/books/ accessed in February 2017.

[13] Sekhar, D.C. & Ganguli, R., *Modified Newton, Rank-1 Broyden Update and Rank-2 BFGS Update Methods in Helicopter Trim: A Comparative Study*, Aerospace Sci. & Tech., **23** (1), pp. 187-200, Dec. 2012.

[14] Dennis, J.E., *On the Convergence of Broyden's Method for Nonlinear Systems of Equations*, Math. of Comp., **25** (115), pp. 559-567, 1971.

[15] Gay, D.M., *Some Convergence Properties of Broyden's Method*, SIAM J. Numer. Anal., **16** (4), pp. 623-630, 1965.

[16] Wu, X., Li, Y., Su, X. & Shang, B., *Application of SPS and TGNET in Natural Gas Pipeline Network Simulation*, Int. Conf. on Pipelines & Trenchless Technology (ICPTT) 2009 http://ascelibrary.org/ accessed in February 2017.

[17] Esfahanian, V., Alavi, S.M., Ashrafi, K., Ghader, S., Ashjaee, M., Ramzmjoo, A. & Samadian, M., *Hydrate Formation Prediction during Discharge of Trapped Natural Gas in a Network. Case Study: Tehran City Gas Network*, Proceeding of the 3rd International Gas Processing Symposium, Qatar, pp. 374-382, March 5-7, 2012.

[18] Stoner, M.A., *Steady-State Analysis of Gas Production, Transmission and Distribution System*, paper SPE 2554 presented at the SPE 44th Annual Fall Meeting, Denver, Colo. USA, Sept. 28 – Oct. 1, 1969.

[19] Ikoku, C.U., *Natural Gas Production Engineering*, John Wiley & Sons, New York, 1992.