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파이프라인 네트워킹 최적화 모델의 개발 및 활용

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Development and Application of Pipeline Network Optimization Simulator

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요　약

본 연구에서는 실제현장에 활용할 수 있는 가스파이프라인 네트워크의 최적화 모델을 개발하기 위해 먼저 구조 설계에 있어서 네트워크 알고리즘 중 MCST(Minimum Cost Spanning Tree) 알고리즘을 도입하여 전반적인 구조를 결정하고, 기존 방법의 단점을 보완하기 위해 Constrained Derivative 방법을 적용하였다. 또한 모델 개발 시, 압축기 · 밸브 등의 갑작스런 운전상태의 변화와 파이프의 파열 등으로 인한 유동저해 현상을 예측할 수 있는 파이프라인 해석모델과 연계할 수 있도록 고려하여 설계하였다. 각 절점과 간선간의 압력 및 유량, 즉 파이프라인 배관망에서 필요한 수요량을 적절히 공급할 수 있는 파이프라인 망의 직경과 길이를 최소의 비용으로 결정하는 복합형 파이프라인 네트워크 최적설계 모델을 개발하였다. 개발된 모델을 전형적인 천연가스 파이프라인 네트워크에 적용하여 최적설계를 수행한 결과, 보다 작은 파이프 직경과 낮은 절점 압력으로도 각 절점에서의 수요량을 공급할 수 있도록 설계할 수 있었으며, 원래의 시스템과 비교하여 약 40%정도의 비용 절감효과를 볼 수 있었다. 또한, 기존의 국내 수도권 배관망에 대해 본 모델을 적용하여 새로운 설계모형을 제안함으로써 초기설계나 향후 추가 확장되는 부분의 배관망에 대해서도 경제성을 고려하여 최소비용의 네트워크 구성을 할 수 있음을 확인하였다.

Abstract - This paper presents a hybrid network model(HY-PIPENET) implementing a minimum cost spanning tree(MCST) network algorithm to be able to determine optimum path and constrained derivative(CD) method to select optimum pipe diameter. The HY-PIPENET has been validated with the published data of 6-node/7-pipe network. Networking system and also this system has been optimized with MCST-CD method. As a result, it was found that the gas can be sufficiently supplied at the lower pressure with the smaller diameters of pipe compared to the original system in 6-node/7-pipe network. Hence, the construction cost was reduced about 40% in the optimized system. The hybrid networking model has been also applied to a complicated domestic gas pipeline network in metropolitan area, Korea. In this simulation, parametric study was performed to understand the role of each individual parameter such as source pressure, flow rate, and pipe diameter on the optimized network. From the results of these simulations, we have proposed the optimized network as tree-type structure with optimum pipe diameter and source pressure in metropolitan area, Korea.

however, this proposed system does not consider the environmental problems or safety concerns.

Key words : gas, pipeline network, optimization, simulation, constrained derivative(CD) minimum cost spanning tree(MCST)

1. INTRODUCTION

The role of natural gas as a clean energy source, especially in the non-transportation sector, is increasingly growing. A dramatic increase of gas consumption obviously yields more construction of natural gas pipeline transportation system.

Several investigators[1, 2, 3, 4, 5] have attempted optimization problems for the pipeline net-work in many different ways, however, these researches have been concerned for the straight pipeline system with no branches or for the already designed networking system. Larson and Wong[1] have optimized the inlet and outlet pressures of compressing stations under fixed conditions of diameter and length of pipe, and number of stations as well, in straight pipeline system. Martch and McCall[2] have improved the previous model[1] by adding branches that form a network. They have with the system involving seven different employed both parallel and series connections size of diameter. In their model, networking study has been conducted by using experience rules, however, there are many numbers of cases as 7^{N-1} for (N-1) pipeline section system. Cheeseman[3] and Graham et al.[4] have attempted a network optimization with a commercial program which is excessively focused on resolving pressure distribution for the single phase gas network in steady state flow. The univariate searching method used in their method is not appropriate for optimizations having constraints condition. As an improved method, Flanigan[5] has proposed a multistep optimization for the diameter with the constrained steepest decent method. This method, however, also has a problem because of restrictions in designing the entire network structure.

Along these lines, in order to overcome afore-mentioned problems, this study has proposed a hybrid model(HY-PIPENET) implemented with MCST algorithm for determining network structure and with CD method for optimizing the diameter. The model developed in this study has been validated and optimized for a 6-node/7-pipe network. Finally, the model has been applied to actual pipeline network system in metropolitan area, Korea, and we have proposed a new network system without considering aspects of environmental problems and safety concerns.

2. NETWORKING THEORY AND MODEL DEVELOPMENT

The network is a special form of data structure calling graph, and the graph theory was first introduced by Euler in 1736 to solve problem of a bridge in Königsburg. Several studies[6, 7] have been done on the graph theory, and then optimization theory over the network system has begun in the 1950s. These studies have progressed rapidly with the advances in the field of linear programming.

In general, networking algorithm is described as follows: For a network with N nodes as illustrated in Fig. 1, a spanning tree has a group of (N-1) sections connecting all nodes not as a loop. For the optimization of this system, a weighting factor(distance cost of link) is given to each section and a subgraph is then determined as connected all nodes such that sum of length of the section is minimum. This subgraph should not contain the loop to keep a minimum cost, however, if there exists a loop between the nodes, only one path having minimum weight should be taken. In this work, MCST algorithm is employed, first, to select a minimum spanning tree between two nodes with the lowest cost.

Then, a minimum spanning tree containing three nodes is selected from the resulted tree-type structure with two nodes. This

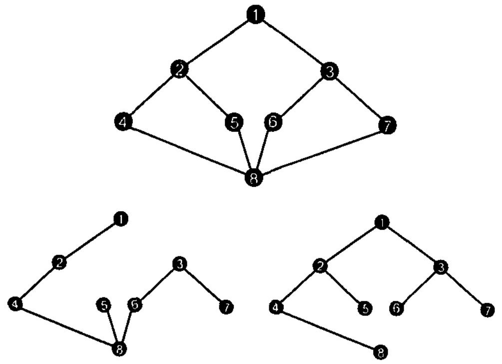

Fig. 1. Examples of the spanning tree

process is repeated until all the nodes are connected as shown in Fig. 2. Once minimum cost spanning tree from all nodes are determined, CD method is then applied to optimize pipe diameter. In this CD method[5], an objective function(cost function) and a flow equation(constraint equation) can be defined as follows:

Cost function;

$$y = \sum_{i}^{N-1} C_i \cdot D_i \tag{1}$$

Constraint equation of Node m;

$$f_m = Q_{j-m} - Q_{m-k} - Q_m \tag{2}$$

Where y and f are functions of decision and state variables, respectively. Subscript i in equation 1 represents pipe section, and in equation 2, m is nodal number. Subscripts j and k are neighboring nodes of Node m, and j_m and m_k represent pipe sections between nodes j and m, and nodes m and k, respectively. In the CD method, in order to obtain δy, derivatives for each decision variable should be computed in the following manner:

$$\frac{\delta y}{\delta d_l} = \frac{|A|}{|B|} \tag{3}$$

Where $\delta y / \delta d_l$ is the constrained derivative of cost function with respect to decision variable d_l. In this equation, $|A|$ and $|B|$ represent determinants of Jacobian matrix for objective function y and constraint equation f, respectively. The result of equation 3 means total change of cost function caused by a change for each decision variable. Therefore,

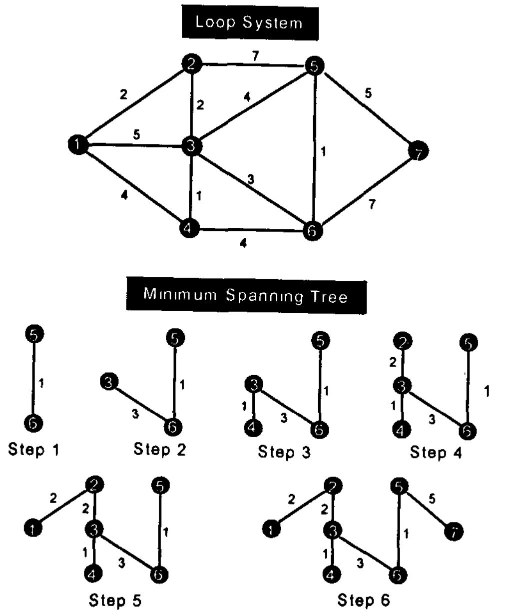

Fig. 2. Schematic procedure for finding a minimum spanning tree in MCST algorithm

in the system with several decision variables, the sophisticated approach should be applied to determine the relative change of each variable. The simple method of steepest descent has been widely used to accomplish these problems, mathematically this method can be expressed by the following form[8]:

$$\Delta d_l = -\eta \frac{\delta y}{\delta d_l} \tag{4}$$

Where Δd_l is the change in decision variable of d_l, and η is a constant multiplier. Once the value of η and the new values of d are calculated, the constrained derivatives are computed and tested to check whether the optimum has been reached. In this process, the optimum occurs when all of the constrained derivatives become near to zero.

In optimization problem, since the flow system should be always in balance, material balance equations are used as constraints. In this study, Panhandle A formula for pipeline flow was adapted[9]. In order to obtain solution of material balance equations, Newton-Raphson procedure was utilized in the following matrix form[10]:

$$[B][\Delta S]=[-f] \quad (5)$$

In this equation, B represents Jacobian matrix for constraint equation of f, and S is state variable. With the aid of theory described previously, a pipeline networking model was programmed for optimizing the natural gas pipeline network system.

3. VALIDATION AND APPLICATION OF HY-PIPENET

3.1. 6-Node/7-Pipe Network.

In this section, we first performed validation of the model and the optimization with MCST-CD pipeline networking model on the 6-node/7-pipe network system(Fig. 3) conducted by Flanigan. Fig. 3 shows a six nodal system in which gas is transported from one supplying base(Node 6) to four delivering nodes(Node 1, 2, 3 and 4). As can be seen in this figure, all the data used in the model such as diameter, length, source pressure, amounts of gas demand and supply are given. It is assumed that flow efficiency is 92% and construction cost of pipeline is $-4,000/inch-mile. Based on these data, the HY-PIPENET was validated by comparing the optimum-designed results of Flanigan's work(CD method). Once the model was validated, it was utilized to optimize above system by using MCST-CD method proposed by this work.

In the results tested for the validity of the developed model, as shown in Figs. 4 and 5, it is found that pipe diameter, length, nodal pressure as well as network structure are excellently matched with Flanigan's results. This time, we compared above results obtained by CD method against the results from the model using MCST-CD method. As presented in Fig. 6, the pipeline sections of Node 1-2 and Node 2-4 are eliminated comparing to original system. Also in this figure, one can find that the demanded amount of gas can be sufficiently supplied

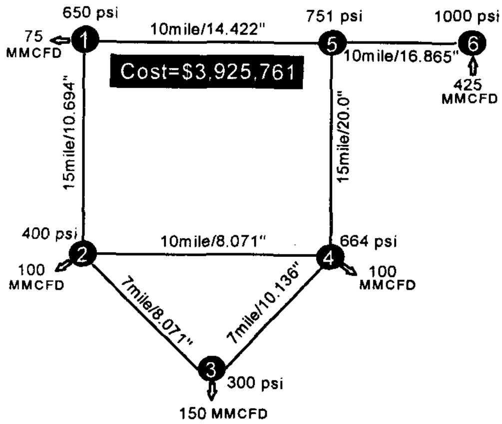

Fig. 3. Original network with 6-node/7-pipe

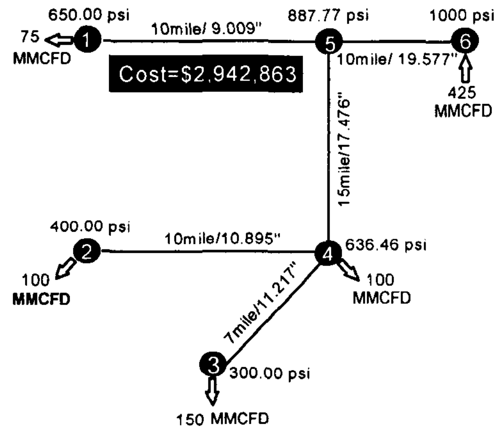

Fig. 4. The optimized result by CD method proposed by Flanigan

even with the lower nodal pressure. The loop structure(original system) has an advantage in general that it can be more smoothly supplied, nevertheless, this structure costs more in construction than the optimized system. That is, $ 2,864,526/inch-mile in the optimized system by MCST-CD method against $ 3,925,761 in original system. On the other hand, when the system is optimized only by CD method, the costs of both Flanigan's work and this study are very similar to each other, however, they are greatly different against original system($ 3,925,961 of original system versus $ 2,953,435 of this system).

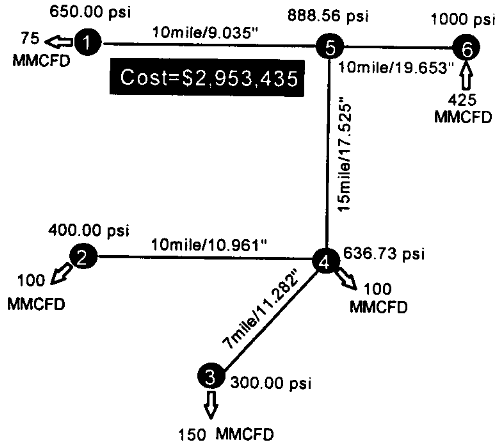

Fig. 5. The optimized result by CD method using HY-PIPENET model

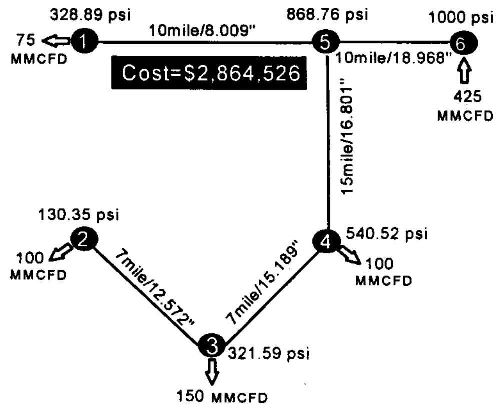

Fig. 6. The optimized result by MCST-CD method using HY-PIPENET model

3.2. Application of HY-PIPENET to Metropolitan Area, Korea

The LNG network in metropolitan area is structured as a loop system, and it is designed to be able to supply continuously in any future circumstances, such as gas leakage, blowout, dramatic increase of gas demand, etc. However, in the case of loop system, high source pressure in pipeline is required, yielding a significant increase in construction cost. Therefore, in this study, we tried to perform the optimization of an actual system with the MCST-CD networking model, that is, metropolitan area in Korea which is currently operated by Korea Gas Corp. In this optimization sudy, it was designed without considering environmental problem or emergency situations such as gas leakage and blowout.

In metropolitan pipeline looping system(Fig. 7), LNG stored at Pyongtaek terminal is pressurized by a pump up to 955 psi and vaporized to be delivered to each station in the metropolitan area and also to Taejon. The delivered high-pressured gas is then depressurized at Mokkam, Daechee, Kajwa, Hapjung, Ilsan and Kunja stations. The data used in these simulations are based on Jan. 13, 1995, and these data(pipe diameters and lengths) are listed in Table 1.

The coefficients of the cost function were computed with the assumption of $ 35,942,167 in this loop system. Fig. 7 shows the pipeline network in the metropolitan area and this is schematically graphed for simulational work. As shown in this figure, the pipeline system consists of 30 nodes and 36 pipe sections, and it is connected as a loop system in which many circular routes

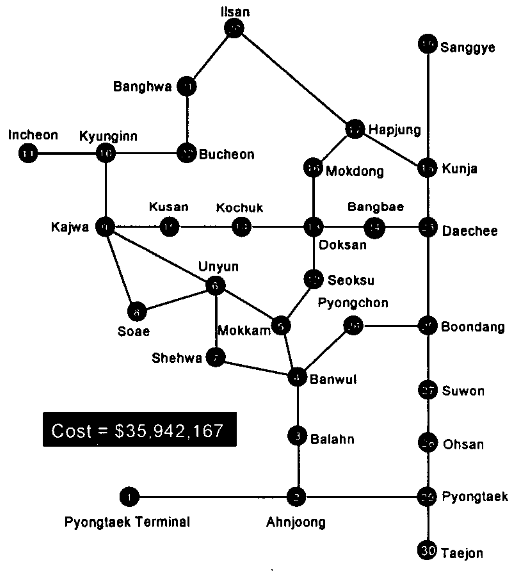

Fig. 7. Original Gas pipeline network in metropolitan area, Korea

are included.

By applying the actual data into a MCST-CD network model, the optimized results are given in Table 1 and the resulting optimized structure is presented in Fig. 8. In this figure, pipeline sections of Ahnjoong-Balahn, Pyongchon-Boondang, Kochuk-Kusan, Unyun-Mokkam, Kajwa-Soae, Kyunginn-Kajwa and Hapjung-Kunja were eliminated and the total cost was greatly reduced by $ 15,800,000 (from $ 35,942,167 to $ 20,112,378). Also, as presented in Table 1, pipe diameters are significantly decreased. This is because current original system was designed for the stable supply of gas, and therefore large size of pipe diameters with high source pressure was used. It means that the optimized system can supply current gas demand sufficiently with the lower source pressure and the smaller diameter of pipe. However, this system did not consider emergency situations at all.

In order to investigate effect of source pressure on the gas supply, simulations were conducted for the optimized network and pipe diameter. In these runs, we attempted to find the minimum source pressure which can supply the gas sufficiently at Pyongtaek terminal(current source pressure is 955 psi at the terminal). The results of these runs are presented in Fig. 9. As can be seen in this figure, in the case of 955 psi, pressures at all sites are almost close to 955 psi of source pressure at terminal and one can realize that the source pressure(955 psi) is too high at the current gas demands. However, when the source pressure is dropped down to 350 psi, this system can not supply gas at Kyunginn(Node 10), Incheon (Node 11), Mokdong(Node 16), Hapjung(Node 17), Ilsan(Node 20), Banghwa(Node 21) and Bucheon (Node 22). Therefore, it is found that the source pressure at the terminal can be as low as about 360 psi for the optimized system. This time, a series of simulations were conducted to examine the amount of gas flow rate in the existing network system. In these simulations, the optimized network system with a source pressure of 360 psi at the terminal was used by applying the actual pipe diameter currently constructed. Fig. 10 shows that when the supplying rate is increased up to 5.2 times the current rate, gas demands can not meet at Kyunginn(Node 10), Incheon(Node 11), Mokdong(Node 16), Hapjung(Node 17), Ilsan(Node 20), Banghwa (Node 21) and Bucheon(Node 22). Therefore, the optimized system with source pressure of 360 psi can satisfy supplying rate up to about five times greater than the current rate

Table 1. Pipe Diameters and lengths for original and optimized systems

Pipe Section No.	Node	Original		Optimized	
		D(inch)	L(mile)	D(inch)	L(mile)
1	1- 2	25.1890	9.51505	14.2390	9.51505
2	2-29	28.8110	9.94194	16.2865	9.94194
3	29-28	25.1890	12.42740	13.7659	12.42740
4	28-27	25.1890	9.94194	13.7659	9.94194
5	27-25	39.3662	10.87400	21.1040	10.87400
6	25-26	25.1890	13.67020	N.C.	
7	25-23	25.1890	11.80600	13.1127	11.80600
8	26- 4	25.1890	9.94194	11.1278	9.94194
9	4- 3	25.1890	10.36570	14.5939	10.36570
10	3- 2	25.1890	13.60060	N.C	
11	4- 7	28.8110	6.83508	15.3220	6.83508
12	4- 5	25.1890	6.88790	14.6011	6.88790
13	7- 6	28.8110	6.83508	15.3220	6.83508
14	5-12	23.0709	6.57348	10.9140	6.57348
15	5- 6	25.1890	7.54282	N.C	
16	12-13	19.3780	6.79656	9.4492	6.79656
17	13-24	23.0709	6.21371	12.2431	6.21371
18	24-23	23.0709	6.21371	12.2431	6.21371
19	23-18	23.0709	9.22052	10.6775	9.22052
20	18-19	19.3780	7.42041	8.2214	7.42041
21	13-14	19.3780	6.21371	19.3780	6.21371
22	14-15	19.3780	7.61614	N.C	
23	15- 9	19.3780	6.82762	19.3780	6.82762
24	9- 8	28.8110	6.83508	N.C	
25	8- 6	28.8110	6.83508	15.0823	6.83508
26	6- 9	19.3110	6.21371	10.2854	6.21371
27	18-17	19.3780	10.26130	N.C	
28	13-16	19.3110	8.46929	9.4253	8.46929
29	16-17	19.3110	3.41754	8.5450	3.41754
30	17-20	25.1890	7.45645	10.2678	7.45645
31	20-21	25.1890	6.21371	13.5177	6.21371
32	21-22	25.1890	6.83508	13.5177	6.83508
33	22-10	25.1890	6.47948	25.1890	6.47948
34	9-10	19.3110	9.93324	N.C	
35	10-11	19.3110	9.32056	19.3110	9.32056
36	29-30	28.8110	65.74110	28.8110	65.74110

N.C.: Not Connected

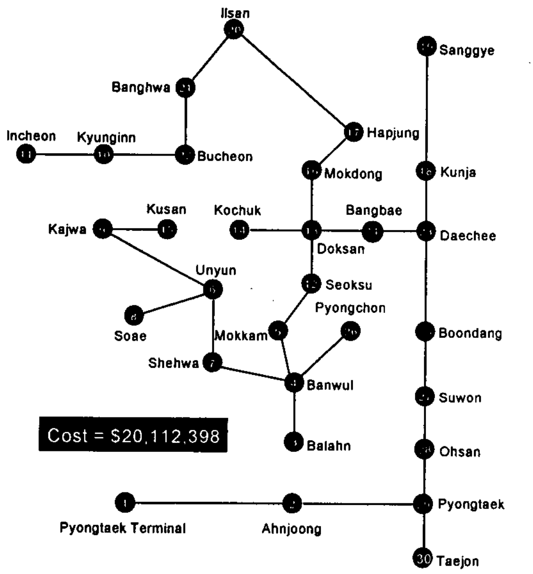

Fig. 8. The optimized gas pipeline network in metropolitan area, Korea

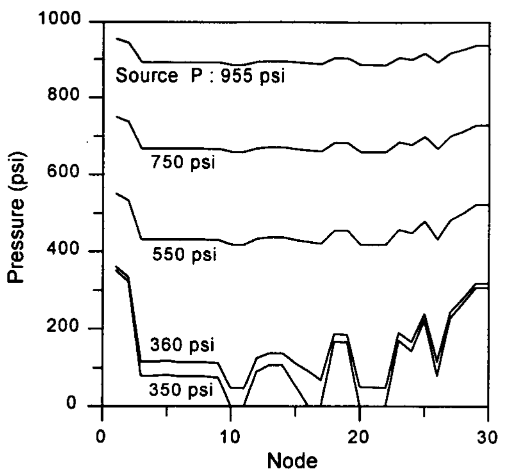

Fig. 9. Effect of source pressure on the nodal pressure

under the condition of actual pipe diameter. However, when source pressure is used as original pressure(955 psi) with the optimized network, the system with actual pipe diameter can support as much as 14 times greater than the current supplying rate(Fig. 11).

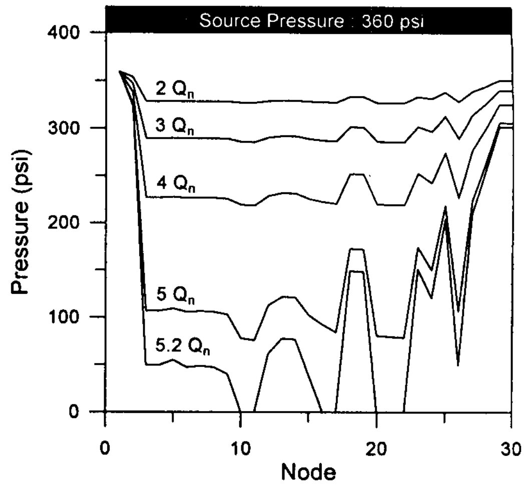

Fig. 10. Effect of flow rate on the nodal pressure

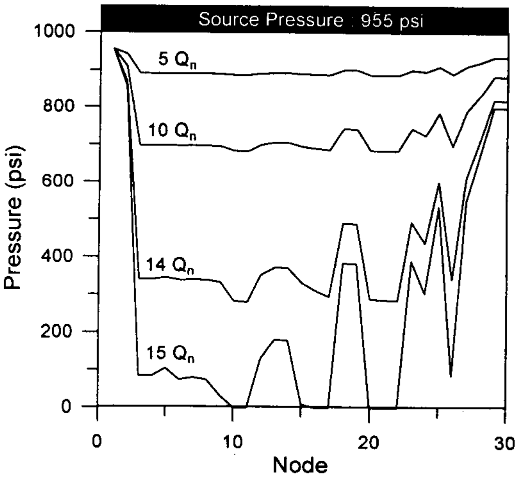

Fig. 11. Effect of flow rate on the nodal pressure

4. CONCLUSIONS

In order to design optimum pipeline network system, pipeline network model(HY-PIPENET) was developed by adapting MCST algorithm to determine optimum structure and CD algorithm to determine optimum pipe diameter. The developed model was validated and optimized by using the published data. Also, the model was applied to actual system of metropolitan area in Korea. Form the results of investigations presented in this paper, the following conclusions may be drawn:

1. In the testing results for validity of the model(HY-PIPENET) only by using Cd method, it was found that pipe diameter, length, nodal pressure as well as network structure are excellently matched with the published data in 6-node/7-pipe network system.

2. Again, in 6-node/7-pipe network system, we have attempted the optimization by using hybrid MCST-CD network model. As a result, network structure was simplified with the lower nodal pressure. The results are very much cost-effective in construction comparing to the original system.

3. This time, we have applied HY-PIPENET model to LNG pipe network system in metropolitan area, Korea. From the results, we have found a new tree-type network system which is able to satisfy gas demand of current metropolitan area at the lower source pressure and the smaller pipe diameter.

4. In order to investigate effect of source pressure on the gas supply, simulations were conducted for the optimized network system and the optimized pipe diameter. We found a minimum source pressure which can supply gas demand sufficiently at Pyongtaek terminal (current source pressure is 955 psi at the terminal). With the optimized network system, it was found that the source pressure at the terminal can be as low as about 360 psi in metropolitan area.

5. Finally, we have conducted simulations with various source pressures to estimate the supplying ability of the optimized metropolitan network system with current pipe diameters. When source pressure was used as original pressure of 955 psi with the optimized network structure, current pipe diameter system could support as much as 14 times greater than the current supplying rate.

NOMENCLATURE

C = *coefficient of cost function*
D = *pipe diameter*
Q = *gas flow rate*

SI METRIC CONVERSION FACTORS

ft	× 3.048*	E-01 = m
in.	× 2.54*	E+00 = cm
mile	× 1.609 344*	E+00 = km
psi	× 6.894 757	E+00 = kPa

* Conversion factor is exact

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