Modeling of residual chlorine for water distribution network for a pilot village

R. Shreedhar

Abstract— Water is the most essential thing in this world for the survival of living species. The treatment of water is necessary before it is sending to consumer point. The treated water from the treatment plant travels through a water distribution network. Due to some chemical and biological factors of source water, lack of effectiveness and efficiency in treatment processes, improper way of maintenance and mixing of water from different sources within a distribution network and other hydraulic conditions in distribution, people are not getting good quality water. Especially in villages people are facing problems to get good quality drinking water and sometimes they face shortage of drinking water.Hence, the present study is taken to design the water distribution network of a pilot village in northern part of Karnataka state, India for the assessment of drinking water before it is used. For this, one of the standard software i.e., EPANET is used to analyze the water distribution network. Chlorine is injected at the tank with a constant concentration of 1.0 mg/l. Thus chlorine residual concentration values remain quite high (≥ 0.60 mg/l). For the considered water distribution network, the chlorine residual concentration values computed during the last two days of the simulation remain greater than the minimum admissible range of 0.3 mg/l.

Index Terms— Chlorine residual, EPANET, Simulation, Water distribution system, water quality

1 Introduction

Static analysis of a water distribution network provides instantaneous pictures of the pipe discharges and nodal heads. Hardy cross, Newton-Raphson, Linear theory and Gradient methods used for static analysis of distribution network. Dynamic analysis provides variation of pipe discharges and nodal head considering changes in discharge tank levels, valve settings, flow reversals in pipe and rapid demand changes. Both static and dynamic analysis techniques are used to developing models for chlorine residual.

• R,Shreedhar is currentlyAssociate Professor in Civil EnginneringDepartment at KLS Gogte Institute of Technology, Belagavi, Karnataka, India affiliated to Visvsevaraya Technological Universiy (VTU), Belagavi. He is presently persuing his PhD
PH-919845005722 E-mail: rshreedhar@git.edu

Advection (movement in the direction of flow) and dispersion (movement in the direction due to concentration difference) are the two important mechanisms for transportation of residual chlorine. The basic equation describing advection-dispersion transport is based on the principle of conservation of mass and Fick's law diffusion.

Different substances present in water have different potential to react with chlorine i.e., some substances react much more rapidly than others. It is impractical to model all these reactions separately. Therefore simplified decay mechanisms are considered in practice. The mechanism of chlorine decay in pipe has two dimensions. The first dimension is the reaction of chlorine with substances present in water. This decay of

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chlorine is known as bulk decay. The second dimension is the reaction of chlorine with substances present on pipe wall. Pipe water quality, and treatment techniques. This decay of chlorine is known as wall decay. The wall decay in distribution networks may be predominant where significant corrosion is present.

The loss of disinfectant residual in drinking water distribution systems is a major concern for water utilities. Disinfectant residual decay in distribution systems is caused by reactions of chlorine with compounds present in the bulk liquid as well as reactions with the pipe surface, iron corrosion products and biofilms on the pipe wall (Biswas, Lu and Clark 1993; Rossman, Clark and Grayman 1994). Chlorine decay in the bulk liquid has been found to be best described using a firstorder kinetics model with respect to initial chlorine concentration. However, this approach has been found to be site specific and do not explain the discrepancies between kinetic constants observed for different waters (Powell et al. 2000b). Some studies have found the kinetic constants for reactions in the bulk liquid to be dependent on the water quality parameters such as temperature and organic content of the water (Kiéné, Lu and Lévi 1998, Hua et al. 1999). Kiéné, Lu and Lévi (1998) used a first-order model with respect to chlorine dose to model bulk chlorine decay with a rate constant (Kb) that is dependent on total organic content (TOC) and temperature. The pipes normally used in distribution systems can be classified in two groups: synthetic pipes and metallic pipes. The chemical and biological characteristics and reactions on the interior wall gets frequently coated with variety of scales whose composition depends on pipe type, source pipe walls vary significantly by group. Previous studies have reported that synthetic materials such as PVC, medium and high-density polyethylene, cement lined iron and polypropylene have a very low chlorine demand (Kiéné et al. 1998, Hallam et al. 2002). Metallic pipes have high chlorine demand and chlorine decays as chlorine reacts with the elemental metal or the associated corrosion products on the pipe wall, especially in unlined cast iron pipes. Free chlorine reacts chemically with the walls of cast iron pipes and the total chlorine consumption rate could be calculated based on the corrosion current density (Frateur et al. 1999).

EPANET is a computer program that performs extended period simulation of hydraulic and water quality behavior within pressurized pipe networks. A network consists of pipes, nodes (pipe junctions), pumps, valves and storage tanks or reservoirs. EPANET tracks the flow of water in each pipe, the pressure at each node, the height of water in each tank, and the concentration of a chemical species throughout the network during a simulation period comprised of multiple time steps.

In addition to chemical species, water age and source tracing can also be simulated. EPANET is designed to be a research tool for improving our understanding of the movement and fate of drinking water constituents within distribution systems. It can be used for many different kinds of applications in distribution systems

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analysis. Sampling program design, hydraulic model calibration, chlorine residual analysis, and consumer exposure assessment are some examples. EPANET can help assess alternative management strategies for improving water quality throughout a system.

2.0 Water distribution network for a pilot village

The water distribution layout for a pilot village consists of a tank, 35 nodes, and 41 pipes. The distribution network is analyzed by EPANET for projected population of 3883 with a peak factor equal to 4. The designed pipeline for the network is as shown in Figure1.0

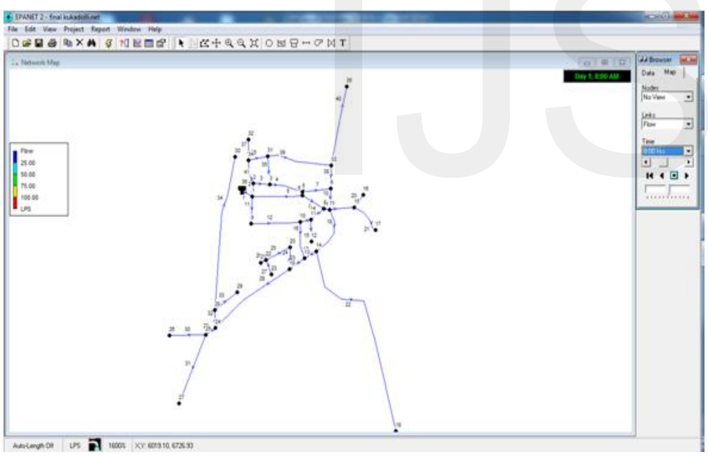

Figure 1.0 Water distribution network for a pilot village

The distribution network is analyzed with minimum pressure head of 7.5m at the source (tank) and the pressure at each of the junctions is tabulated in Table 1.0. It is seen from Table 1.0, a minimum pressure of 4m is maintained at almost all the junctions except for tail end junctions. The diameter of the pipe, length of the pipe considered and flow in each pipe are obtained and tabulated in Table 2.0. The negative sign for flow indicates that the flow is in opposite direction.

Table 1.0 Pressure at various nodes

Network Table - Nodes at 0:00 Hrs			
Node ID	**Elevation (m)**	**Head (m)**	**Pressure (m)**
Junc 1	665.23	671.18	5.95
Junc 2	664.77	671.17	6.40
Junc 3	664.38	671.14	6.76
Junc 4	663.75	671.13	7.38
Junc 5	662.07	671.12	9.05
Junc 6	660.91	671.08	10.17
Junc 7	660.04	671.05	11.00
Junc 8	659.01	671.05	12.04
Junc 9	665.89	671.17	5.27
Junc 10	662.930	671.05	8.12
Junc 11	660.0	671.05	11.05
Junc 12	662.35	671.05	8.70
Junc 13	662.11	671.02	8.92
Junc 14	660.68	671.03	10.35
Junc 15	659.26	671.04	11.78
Junc 16	658.20	671.04	12.84
Junc 17	657.11	671.04	13.94
Junc 18	668.82	671.02	2.20
Junc 19	663.56	670.91	7.35
Junc 20	663.96	670.90	6.94
Junc 21	663.80	670.90	7.10
Junc 22	663.85	670.90	7.05
Junc 23	663.65	670.90	7.25
Junc 24	663.73	670.54	6.81
Junc 25	665.44	670.52	5.09
Junc 26	665.12	670.51	5.39
Junc 27	665.00	670.51	5.51
Junc 28	667.71	670.41	2.70
Junc 29	666.57	670.41	3.84
Junc 30	665.41	670.33	4.92
Junc 31	663.34	671.12	7.78
Junc 32	662.07	671.16	9.09
Junc 33	666.76	671.09	4.32
Junc 34	663.31	671.16	7.85
Junc 35	659.09	671.07	11.98
Tank 36	663.75	671.25	7.50

Table 2.0 Diameter of pipes and Flow in each pipe

Link ID	Length (m)	Diameter (mm)	Flow (LPS)
Pipe 1	35	200	20.81
Pipe 2	30	200	7.13
Pipe 3	45	140	3.96
Pipe 4	90	140	2.17
Pipe 5	130	200	8.14
Pipe 6	10	140	2.19

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Pipe 7	78	140	3.79
Pipe 8	87	140	5.08
Pipe 9	10	200	2.24
Pipe 10	51	140	4.45
Pipe 11	66	200	5.54
Pipe 12	130	140	5.12
Pipe 13	32	200	-2.23
Pipe 14	46	200	2.78
Pipe 15	56	140	0.35
Pipe 16	92	200	6.54
Pipe 17	38	140	-2.23
Pipe 18	120	200	4.97
Pipe 19	64	140	1.18
Pipe 20	40	140	0.25
Pipe 21	85	140	0.35
Pipe 22	300	200	1.87
Pipe 23	50	140	8.65
Pipe 24	55	140	-1.4
Pipe 25	72	140	0.95
Pipe26	40	140	0.25
Pipe27	40	140	0.25
Pipe28	240	110	6.94
Pipe29	29	90	2
Pipe30	105	140	7.57
Pipe31	186	140	3.51
Pipe32	43	140	4.89
Pipe33	74	90	9.43
Pipe34	385	110	6.92
Pipe35	71	140	8.55
Pipe36	51	140	10.58
Pipe37	50	140	2.99
Pipe38	51	90	5.85
Pipe39	175	110	10.4
Pipe40	195	90	5.57
Pipe41	66	140	12.73

Water quality analysis are performed in EPANET over a 24 hours period of time, using a hydraulic time step of 1 hour and a water quality time step of 0.02 minutes. Final data are reported at three time moments, namely at 6 am (average daily consumption), at 3 am (off-peak) and 8 am (first peak hour). The flow rate *Qj* in l/s, the rate of reaction *rj* mg/(l-day) and the chlorine concentration *Cj* in mg/l, at 6a.m., 3a.m. and 8a.m without the demand pattern is as shown in Table 3.0.

The chlorine concentration distributions on the water network pipes at 3a.m. and 8a.m. are plotted in figure 2.0 and figure 3.0.

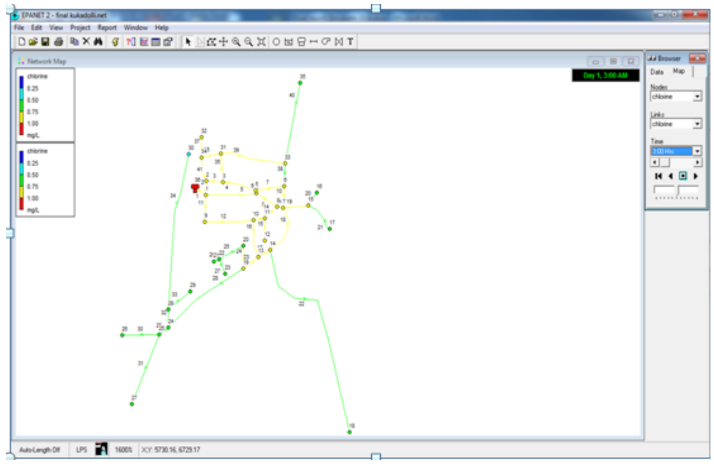

Figure 2.0 Flow direction & chlorine residual concentration distribution at 3 am

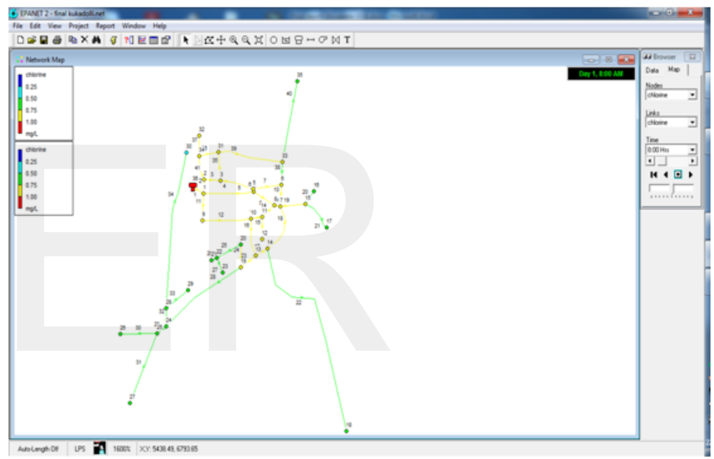

Figure 3.0 Flow direction & chlorine residual concentration distribution at 8 am

A variable water demand is also considered over a 24 hours period of time pattern with one hour time step, using the pattern coefficients $c(t)$ as shown in Table 4.0 , for each time t , starting at midnight (those coefficients are multiplying the input flow and all base demand values reported for the average daily water consumption).

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Table 4.0 Coefficients of demand patterns c (t) at time t

t	c(t)
12 am	0.36
1.00 am	0.36
2.00 am	0.36
3.00 am	0.36
5.00 am	0.60
6.00 am	0.84
7.00 am	1.00
8.00 am	1.32
9.00 am	1.44
10.00 am	1.50
11.00 am	1.44
12.00 noon	1.32
1.00 pm	1.32
2.00 pm	1.32
3.00 pm	1.44
4.00 pm	1.32
5.00 pm	1.44
6.00 pm	1.32
7.00 pm	1.20
8.00 pm	0.90
9.00 pm	0.72
10.00 pm	0.48
11.00 pm	0.48

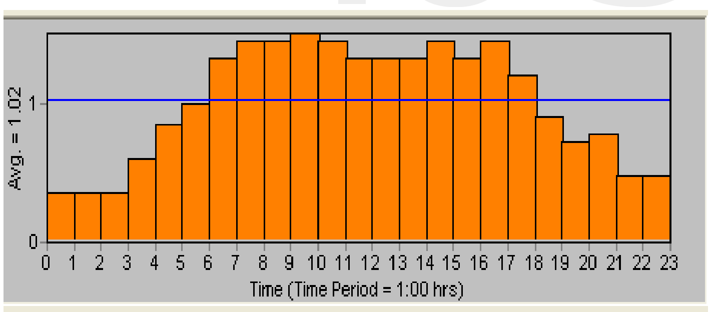

Figure 6.4 Coefficients of demand patterns c (t) at time t

The flow rate *Qj* in l/s, the rate of reaction *rj* mg/ (l-day) and the chlorine concentration *Cj* in mg/l, at 6a.m., 3a.m. and 8a.m for the demand pattern is as shown in Table 5.0

Chlorine is injected at the tank with a constant concentration of 1.0 mg/l. Reactions occurring in the bulk flow, as well as pipe wall reactions are modelled with first-order decay laws. Assuming a variable water demand over a 24 hour's period, Hydraulic and Water Quality analysis is performed in EPANET, to obtain the time dependent flow rate, as well as the time dependent rate of reaction and chlorine residual concentration on network pipes. Thus chlorine residual concentration values remain quite high (≥ 0.60 mg/l). For the considered water distribution network, all chlorine residual concentration values computed during the last two days of the simulation remain greater than the minimum admissible range, which 0.3 mg/l.

3.0 CONCLUSION

Controlling the residual chlorine concentration is very important in drinking water distribution network system. The water quality models to water distribution system gives well calibrated hydraulic model to be used along with the specific reaction rate. The residual chlorine concentration decay in distribution network is designed for three villages. The pilot village is having its projected population of 3883, 41 pipes, tank, and 35 junctions. The chlorine is injected to the tank, with a constant concentration of 1 mg/l.

The reaction occurring in the bulk, as well as pipe wall reactions are modeled with first order decay laws. The hydraulic and water quality analysis is performed in EPANET, over 24 hours period of time, to obtain the time dependent flow rate and time dependent rate of reaction and chlorine residual concentration in network pipe. The chlorine concentration is determined for three time moments that is, at 3am, 6am, and 8am. The minimum residual chlorine concentration of pilot village distribution network is 0.60 mg/l.

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4.0 SCOPE FOR FURTHER STUDY

The present study was initiated with an objective to identify a modeling of chlorine residual in water distribution network. It is recommended to carrying out the research work on some of the following issues

1. The reaction of chlorine decay has been analyzed by EPANET in different time operation. The study should be adopted by continuous process although the limitation of total time operation for chlorine decay is 24 hrs. It may be noted that the water should tested in laboratory validation of chlorine concentration as predicted at different junction of pipe network system by EPANET.

2. Modelling of the movement of a non-reactive tracer material like Fluoride through the network over time (ie. tracing the percent of originating from a specific node) using EPANET.

3. To improve the accuracy of simulation outcomes, it is important to evaluate the properties of pipes in a distribution network model and improves the reproducibility of water flow conditions.

4. Modelling the movement and fate of a reactive material as it grows [e.g. a disinfectant by-product (DBP) like Trihalomethanes] or decays (e.g. Chlorine residual) with time using EPANET.

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Table 3.0 Chlorine concentration at different hours

	t=3am			t=6am			8am		
j	Q_j	r_j	C_j	Q_j	r_j	C_j	Q_j	r_j	C_j
	[l/s]	**mg/l-day**	**mg/l**	**[l/s]**	**mg/l-day**	**mg/l**	**[l/s]**	**mg/l-day**	**mg/l**
Pipe1	20.81	14.43	1	20.81	14.43	1	20.81	14.43	1
Pipe2	6.68	9.84	0.98	7.13	9.82	0.97	7.13	9.82	0.98
Pipe3	4.24	14.6	0.95	3.96	14.6	0.96	3.96	14.6	0.96
Pipe4	2.27	10.39	0.91	2.17	10.39	0.91	2.17	10.39	0.91
Pipe5	8.46	10.18	0.96	8.14	10.18	0.96	8.14	10.18	0.96
Pipe6	2.39	10.64	0.93	2.19	10.64	0.93	2.19	10.64	0.93
Pipe7	4.1	13.02	0.88	3.79	13.02	0.88	3.79	13.02	0.88
Pipe8	5.19	15.2	0.91	5.08	15.2	0.91	5.08	15.2	0.91
Pipe9	2.47	4.79	0.88	2.24	4.79	0.88	2.24	4.79	0.88
Pipe10	4.21	12.78	0.8	4.45	12.8	0.8	4.45	12.8	0.81
Pipe11	5.68	8.65	0.97	5.54	8.65	0.97	5.54	8.65	0.97
Pipe12	5.26	15.43	0.92	5.12	15.43	0.92	2.23	15.43	0.92
Pipe13	2.11	4.54	0.84	2.23	4.54	0.84	2.78	4.54	0.84
Pipe14	2.66	5.35	0.87	2.78	5.35	0.87	0.35	5.35	0.87
Pipe15	0.35	2.96	0.81	0.35	2.96	0.81	6.54	2.96	0.81
Pipe16	6.56	8.14	0.85	6.54	8.14	0.85	2.35	8.14	0.85
Pipe17	2.33	8.94	0.75	2.35	8.91	0.75	4.97	8.91	0.75
Pipe18	4.95	6.67	0.79	4.97	6.67	0.79	1.18	6.67	0.79
Pipe19	1.18	6.39	0.75	1.18	6.39	0.75	0.25	6.39	0.75
Pipe20	0.25	0.88	0.71	0.25	0.88	0.71	0.53	0.88	0.71
Pipe21	0.53	3.43	0.71	0.53	3.43	0.71	1.87	15.77	0.76
Pipe22	1.87	3.22	0.66	1.87	3.22	0.66	1.4	6.84	0.7
Pipe23	8.65	15.74	0.79	8.65	15.77	0.79	0.95	4.98	0.76
Pipe24	1.4	6.83	0.76	1.4	6.84	0.76	0.25	0.78	0.66
Pipe25	0.95	4.99	0.7	0.95	4.98	0.7	0.25	0.78	0.7
Pipe26	0.25	0.78	0.78	0.25	0.78	0.66	6.94	13.84	0.66
Pipe27	0.25	0.78	0.78	0.25	0.78	0.66	2	7.57	0.66
Pipe28	6.94	13.84	0.75	6.94	13.84	0.75	0.66	3.51	0.75
Pipe29	2	7.57	0.69	2	7.57	0.69	1.16	4.89	0.69
Pipe30	0.66	3.51	0.63	0.66	3.51	0.63	3.13	9.43	0.63
Pipe31	1.16	4.89	0.61	1.16	4.89	0.61	0.46	2.81	0.61
Pipe32	3.13	9.43	0.70	3.13	9.43	0.69	2.4	6.92	0.69
Pipe33	0.46	2.81	0.64	0.46	2.81	0.64	1.51	8.55	0.64
Pipe34	2.4	6.92	0.58	2.4	6.92	0.57	2.26	10.58	0.57
Pipe35	1.69	8.54	0.91	1.51	8.55	0.91	0.31	2.99	0.91
Pipe36	1.53	10.56	0.90	2.26	10.58	0.91	1.14	5.85	0.91

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Pipe37	0.31	2.99	0.87	0.31	2.99	0.88	2.27	5.57	0.88
Pipe38	0.59	5.85	0.71	1.14	5.85	0.74	0.31	5.62	0.74
Pipe39	2.12	10.4	0.81	2.67	10.4	0.82	2.67	5.6	0.82
Pipe40	1.21	5.57	0.66	1.21	5.57	0.68	1.21	5.57	0.68
Pipe41	2.25	12.73	0.95	2.98	12.73	0.95	2.98	12.73	0.95

Table 5.0 Chlorine concentration at different hours

	t=3am			**t=6am**			**8am**		
j	**Q_j**	**r_j**	**C_j**	**Q_j**	**r_j**	**C_j**	**Q_j**	**r_j**	**C_j**
	[l/s]	**mg/l-day**	**mg/l**	**[l/s]**	**mg/l-day**	**mg/l**	**[l/s]**	**mg/l-day**	**mg/l**
Pipe1	20.81	14.43	1	20.81	14.43	1	20.81	14.43	1
Pipe2	6.68	9.84	0.98	7.13	9.82	0.97	7.13	9.82	0.98
Pipe3	4.24	14.6	0.95	3.96	14.6	0.96	3.96	14.6	0.96
Pipe4	2.27	10.39	0.91	2.17	10.39	0.91	2.17	10.39	0.91
Pipe5	8.46	10.18	0.96	8.14	10.18	0.96	8.14	10.18	0.96
Pipe6	2.39	10.64	0.93	2.19	10.64	0.93	2.19	10.64	0.93
Pipe7	4.1	13.02	0.88	3.79	13.02	0.88	3.79	13.02	0.88
Pipe8	5.19	15.2	0.91	5.08	15.2	0.91	5.08	15.2	0.91
Pipe9	2.47	4.79	0.88	2.24	4.79	0.88	2.24	4.79	0.88
Pipe10	4.21	12.78	0.8	4.45	12.8	0.8	4.45	12.8	0.81
Pipe11	5.68	8.65	0.97	5.54	8.65	0.97	5.54	8.65	0.97
Pipe12	5.26	15.43	0.92	5.12	15.43	0.92	2.23	15.43	0.92
Pipe13	2.11	4.54	0.84	2.23	4.54	0.84	2.78	4.54	0.84
Pipe14	2.66	5.35	0.87	2.78	5.35	0.87	0.35	5.35	0.87
Pipe15	0.35	2.96	0.81	0.35	2.96	0.81	6.54	2.96	0.81
Pipe16	6.56	8.14	0.85	6.54	8.14	0.85	2.35	8.14	0.85
Pipe17	2.33	8.94	0.75	2.35	8.91	0.75	4.97	8.91	0.75
Pipe18	4.95	6.67	0.79	4.97	6.67	0.79	1.18	6.67	0.79
Pipe19	1.18	6.39	0.75	1.18	6.39	0.75	0.25	6.39	0.75
Pipe20	0.25	0.88	0.71	0.25	0.88	0.71	0.53	0.88	0.71
Pipe21	0.53	3.43	0.71	0.53	3.43	0.71	1.87	15.77	0.76
Pipe22	1.87	3.22	0.66	1.87	3.22	0.66	1.4	6.84	0.7
Pipe23	8.65	15.74	0.79	8.65	15.77	0.79	0.95	4.98	0.76
Pipe24	1.4	6.83	0.76	1.4	6.84	0.76	0.25	0.78	0.66
Pipe25	0.95	4.99	0.7	0.95	4.98	0.7	0.25	0.78	0.7
Pipe26	0.25	0.78	0.78	0.25	0.78	0.66	6.94	13.84	0.66
Pipe27	0.25	0.78	0.78	0.25	0.78	0.66	2	7.57	0.66
Pipe28	6.94	13.84	0.75	6.94	13.84	0.75	0.66	3.51	0.75
Pipe29	2	7.57	0.69	2	7.57	0.69	1.16	4.89	0.69
Pipe30	0.66	3.51	0.63	0.66	3.51	0.63	3.13	9.43	0.63
Pipe31	1.16	4.89	0.61	1.16	4.89	0.61	0.46	2.81	0.61
Pipe32	3.13	9.43	0.70	3.13	9.43	0.69	2.4	6.92	0.69
Pipe33	0.46	2.81	0.64	0.46	2.81	0.64	1.51	8.55	0.64
Pipe34	2.4	6.92	0.58	2.4	6.92	0.57	2.26	10.58	0.57
Pipe35	1.69	8.54	0.91	1.51	8.55	0.91	0.31	2.99	0.91
Pipe36	1.53	10.56	0.90	2.26	10.58	0.91	1.14	5.85	0.91
Pipe37	0.31	2.99	0.87	0.31	2.99	0.88	2.27	5.57	0.88
Pipe38	0.59	5.85	0.71	1.14	5.85	0.74	0.31	5.62	0.74
Pipe39	2.12	10.4	0.81	2.67	10.4	0.82	2.67	5.6	0.82
Pipe40	1.21	5.57	0.66	1.21	5.57	0.68	1.21	5.57	0.68
Pipe41	2.25	12.73	0.95	2.98	12.73	0.95	2.98	12.73	0.95