An Overview of the Design Principles of Drinking Water Chlorination

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Abstract- The goal of drinking water chlorination is the inactivation of pathogenic organisms in water. It offers the advantage of producing residuals useful for the preservation of water quality in a distribution system. Basic key chlorination concepts include chlorine demand/decay, chlorine residuals, and CT disinfection. The application of these concepts required a good understanding of the hydraulic condition of the system. Important consideration is the determination of initial required chlorine dose. A demonstration model using a public school water supply scheme with an overhead tank is done. This incorporates the kinematic of Contact Time (CT) disinfection, and the application of a demand model for the determination of initial chlorine concentration/dose required. Optimal application of chlorine will prevent incidences of either an over-doze or under-doze which highlight the importance of this study.

Keywords- chlorine demand, CT Disinfection, initial chlorine concentration, log removal value, residual concentration

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1 INTRODUCTION

Chlorine is the most common chemical disinfectant for water treatment (EPA, 2011), and its typical forms include elementary chlorine, hypochlorite and chlorine dioxide. Elemental chlorine is the pure form of chlorine and comes in either a liquid or gaseous state. In its pure form, elementary chlorine is very reactive, volatile and corrosive, and can be flammable when it reacts with ammonia, requiring dilution for safety purposes. Sodium hypochlorite is the diluted form of elementary chlorine and comes in concentration of 12.5 and 15%, while calcium hypochlorite is the solid form and is available in granules, pallets and powder forms (Pennsylvania Department of Environmental Protection, 2016). Its major strength property is that is produces residual which may remain in water even after disinfection has occurred (WHO, 2017). Disinfection aims at inactivating most of micro-organisms in water essentially the pathogenic ones (Pennsylvania Department of Environmental Protection, 2016). Pathogenic organisms come in form of bacteria, viruses, and protozoa. Important factors that influence their pathogenic activities include: chloride concentration, pH, total organic carbon, dissolved oxygen, hardness, temperature and turbidity (John and Rose, 2005).

Survival rate of micro-organism is also an indicator of their resistance to various disinfection methods as determined using a recommended Log Removal Value (LRV). Micro-organism like protozoa with high resistance to chlorine disinfection exhibits high chlorine demand. Chlorination is most effective against bacteria and viruses and least effective against protozoa (WHO, 2017). Some studies on chlorination of drinking water include: Vasconcelos et al. (1997); Kohpaei and Sathasivan (2011); Casey et al. (2012); and Clark et al. (1989). Vasconcelos et al. (1997) examined chlorine decay within a distribution system using a decay model that incorporates both bulk and wall decay. Kohpaei and Sathasivan (2011) modeled chlorine decay using a parallel second order. They adopted an analytical approach and found the model as suitable. Casey et al. (2012) examined chlorine demand in water obtained using various treatment method, and observed that the demand pattern follows a power correlation function which contradicts generally assumed parabolic pattern.

This study therefore adopts the use of a chlorine demand model for the determination of requirement amount of initial chlorine concentration that will be required for appropriate chlorination. Demand model are generally obtained through laboratory experiment, and is a better approach than the trial and error method.

2 REVIEW OF CHORINATION PRINCIPLES AND FLOW HYDRAULICS

2.1 CT DISINFECTION

CT is simply the measured chlorine concentration in water multiplied by its contact time in water (Rush, 2002). The Baffling Factor (B.F) in equation (1) is indicative of variations between plugged and mixed flow, and it varies between 0 and 1. The measured chlorine concentration in water after a given time is the Residual Free Chlorine (RFC) and is usually determined at the point of the first user, and this mathematically expressed as:

$$CT = RFC\ x\ Contact\ time\ (t)\ x\ B.F \qquad (1)$$

Where,
t is the contact time
B.F is the Baffling Factor
RFC is the Residual Free Chlorine.

Disinfection aims at achieving a target CT level (i.e CTrequired). CTachieved is the provided CT disinfection in the distribution system while CTrequired is the minimum required CT value for inactivation of the micro-biological organisms in water. The general procedure aims at achieving a deactivation ratio CTachieved/CTrequired) exceeding 1.0 (Rush 2002). Table 1 is a useful requirement for the determination of CTrequired. Relevant control variable are temperature, pH and residual concentration. Model (1) presents a useful formulation for the determination of CTachieved. Model equation (2) presents an alternative to (1), and is based on infectivity data (LeChevallier and Kwok-Keung Au., 2004) for Giardia inactivation. This was proffered by Clark, et al., (1989):

$$CT = 0.75\ (0.9847C^{0.1758}pH^{2.7519}temp^{-0.1467}) \qquad (2)$$

Where, C is the disinfectant residual concentration, and $temp$ is the reaction temperature in degrees Celcius.

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Table 1. CT table (EPA, 2011)

Chlorine Concentration (mg/L)	Temperature = 15°C							Temperature = 20°C						
	pH							pH						
	<=6.0	6.5	7.0	7.5	8.0	8.5	9.0	<=6.0	6.5	7.0	7.5	8.0	8.5	9.0
<=0.4	49	59	70	83	99	118	140	36	44	52	62	74	89	105
0.6	50	60	72	86	102	122	146	38	45	54	64	77	92	109
0.8	52	61	73	88	105	126	151	39	46	55	66	79	95	113
1.0	53	63	75	90	108	130	156	39	47	56	67	81	98	117
1.2	54	64	76	92	111	134	160	40	48	57	69	83	100	120
1.4	55	65	78	94	114	137	165	41	49	58	70	85	103	123
1.6	56	66	79	96	116	141	169	42	50	59	72	87	105	126
1.8	57	68	81	98	119	144	173	43	51	61	74	89	108	129
2.0	58	69	83	100	122	147	177	44	52	62	75	91	110	132
2.2	59	70	85	102	124	150	181	44	53	63	77	93	113	135
2.4	60	72	86	105	127	153	184	45	54	65	78	95	115	138
2.6	61	73	88	107	129	156	188	46	55	66	80	97	117	141
2.8	62	74	89	109	132	159	191	47	56	67	81	99	119	143
3.0	63	76	91	111	134	162	195	47	57	68	83	101	122	146

2.2 LOG REMOVAL VALUE (LRV)

The Log Reduction Value is expressed as the ability of a treatment processes to remove pathogenic microorganisms. High LRVs will automatically require higher CT values. LRVs are categorized according to the different pathogen type e.g LRV for virus, bacteria, and protozoa. This value is determined in the laboratory using equation (3). An LRV of 1 is equivalent to 90% removal of a target pathogen, an LRV of 2 is equivalent to 99% removal and an LRV of 3 is equivalent to 99.9% removal and so on (WRA, 2014; USEPA, 2012).

$$LRV = log_{10}\left[\frac{influent\ pathogenic\ concentration}{effluent\ pathogenic\ concentration}\right] \qquad (3)$$

Many water treatment uses giardia and virus inactivation requirement as standard for water treatment. Table 2 shows a giardia log reduction based on the number of cryst per 100L of obtained. A Giardia 3-log removal generally requires a higher CT value than that for a 2-log. Chlorination is generally most effective against bacteria and viruses and least effective against protozoa (WHO, 2017), and therefore protozoa requirement becomes the critical value. Chlorination technically is not expected to satisfy the full LRV requirement as other treatment process like filtration, sedimentation and coagulation contribute significantly.

Table 2. Required level of giardia log reduction

S/n	Raw water level	Recommended giardia log reduction
1	<1 cryst per 100 litres	3-log
2	1cryst/100L - 10cysts/100L	3-log to 4-log
3	10cryst/100L – 100cyst/100L	4-log to 5-log
4	>100 cryst/100L	>5-log

Source: (Rush, 2002).

2.3 CHLORINE DEMAND

Demand models measures the "chlorine consumption rate" in water over time. The initial added chlorine initially reacts in three ways: (1) irreversibly with manganese, iron and hydrogen sulphide, (2) reversibly with organic matter and ammonia, (3) with water. The reversible reaction in step (2) results in combined chlorine in form of chloramines, while the left over that reacts with water is the RFC. These organic and the inorganic components "eat up" chlorine in water, before leaving residual free chlorine useful for the disinfection treatment of microbial in water. This demand must be satisfied to ensure adequate biocidal treatment. Chlorine demand increases as the RFC decreases, and can be mathematical expressed as:

$$Chlorine\ demand = initial\ \ dose\ (C_0) - \ RFC \qquad (4)$$

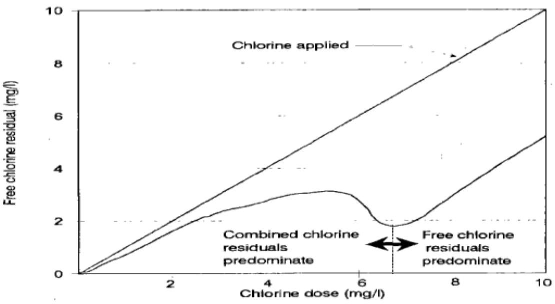

Fig. 1: Breakpoint chlorination

The other approaches requires: (1) breakpoint chlorination (Fig 1) and (2) Chlorine demand model equation (5). Chlorine demand is also measured as the portion in Fig 1, where the combined chlorine residuals predominate, i.e before the rise of the RFC portion of the curve. The model approach adopted for this study follows the power law correlation model (Casey et al. 2012), expressed as:

$$D = \ K_D t^n \qquad (5)$$

Where D is chlorine demand measured in mg/l, t is contact time (mins), K_D and n are empirical fitted coefficient.

2.4 RESIDUAL FREE CHLORINE (RFC)

RFC is portion available for disinfection and is the strong from (Wiant, 2013; Pennsylvania Department of Environmental Protection, 2016). Addition of free chlorine and combined chlorine results in total chlorine. Different test indicators are used in the laboratory to determine the concentration level of both total and free chlorine. To achieve microbial inactivation, the concept of free chlorine residual-time relationship plot must be determined using either a demand or decay curve. Chlorine residual has the advantage of remaining for a longer period of time in a distribution network when compared to ozone which easily decompose but have stronger oxidizing power (National Academy of Sciences, 1977). Residual concentration in a distribution system is required at recommended level to prevent possible re-contamination of the flowing water through pipe wall bio-film.

2.5 HYDRAULIC CONSIDERATIONS

2.5.1 Contact Time

Various microbes in water require different chlorine contact time period for effective disinfection. Adequate contact time must be provided before the water gets to the first consumer. Determination of contact time incorporates the hydraulic flow condition in the tank or pipe network. An ideal Contact time for plugged flow through a conduit pipe network is generally expressed as:

$$Contact\ time\ (mins) = \frac{Volume\ (m^3)*60(\frac{mins}{hrs})}{Peak\ flow\ rate\ (\frac{m^3}{h})} \quad (6)$$

In a real distribution system, this ideal model equation (6) is not suitable for contact tanks since flow through it falls between fully mixed and plug flow. This requires determining the Residence Time Distribution (RTD). EPA, (1999) guideline requires a "Correction Factor (C.F)" or "Baffling Factor (B.F)" which is based on t10 value .Table 3 shows the baffling factors for different tank conditions, while equation (7) shows hydraulic contact time expression incorporating B.F suitable for contact tank.

Table 3. Contact tank baffling factor description

S/n	Condition	t_{10}/ct	Description
1	Unbaffled	0.1	None, agitated Basin, very low length to width ratio, high inlet and outlet velocities
2	Poor	0.3	Single or multiple unbaffled inlet and outlet, no intra-basin baffles
3	Average	0.5	Baffled inlet and outlet with some intra-basin baffles
4	Superior	0.7	Perforated inlet baffle, serpentine or perforated intra-basin baffles, outlet weir or perforated laundaries
5	Perfect	1.0	Very high length to width ration (pipeline flow)

Source: EPA 2011.

$$Contact\ time\ (mins) = \frac{Volume\ (m^3)*60(\frac{mins}{hrs})}{Peak\ flow\ rate\ (\frac{m^3}{h})} * B.F \quad (7)$$

2.5.2 Water demand estimates

This is expressed as the water quantity utilized daily by individual. Factors considered include economic, demographic, weather, and population growth. Water demand estimate is fundamental to the determination of tank size and flow rates. Volumetric flow rates derived using water demand estimate is shown in equation (8).

No	Hydraulic parameters	Value
1	Water demand (W.D)	135liters/capita/day
2	Capacity Factor (C.F)	1.5
3	Peaking Factor (P.F)	2.5
4	Baffling Factor (B.F)	0.3
5	Design population size	2000
6	Hourly Flow rate (based on (8))	16

$$Flow\ rate = Water\ demand\ x\ population\ serviced\ x\ 4.17\ x\ 10^{-5} \quad (8)$$

2.6 CHLORINE DOZING

The expression in (9) shows a typical demand curve with the empirical fitted coefficients determined (Casey et al. 2012). This follows the power law correlation model (5). The treatment category is the chemical coagulation/clarification/filtration of a conventional treatment process. This is a common treatment procedure in many conventional treatment plants, and therefore is adopted for this study.

$$D = 0.387t^{0.252} \quad (9)$$

The initial chlorine dose (C_0) is the amount of chlorine initially added to the distribution system for disinfection purpose and was determined for demonstration model in this study using equation (12).

$$C_0 = RFC + Chlorine\ Demand \quad (12)$$

3 DESIGN METHODOLOGY

3.1 HYDRAULIC CONSIDERATIONS

This model considers a treatment tank at elevation +10m above datum level. An elevation height of 10 meters is expected to provide sufficient hydraulic head for effective water distribution. Hydraulic consideration includes:

1. Determination of required Flowrate: This was determined based on equation (8).
2. Determination of appropriate tank size: This was determined as allowing thrice refilling each day.
3. Determination of Contact time: Model expression (9) and (10) are useful for this purpose.

3.2 DETERMINATION OF $CT_{REQUIRED}$ AND $CT_{ACHIEVED}$

Procedural steps using tables and charts are as follows (Rush, 2002):

1. Determining of required CT: A predetermined LRV of 3 log inactivation was adopted. Table 1 was used for determination of required CT. Similar tables exist for bacteria and virus disinfection, and can be obtained in EPA, (2011).
2. Determining of achieved CT: Relevant models equations include (1), (2), (6) and (7).
3. Comparing CT Values: If $CT_{acheived} > CT_{required}$, then you will have met your disinfection requirement.

3.2 CHLORINE DEMAND

Model equation (9) was used for this purpose with a pH value of 6.73 and temperature 15oC.

3.3 MODEL DESIGN

Relevant hydraulic design data useful for this design is presented in Table 4.

4 DESIGN RESULT AND DISCUSSION

Table 5.0 shows the required tank size for a population of 2000 people with an option of thrice filling of the tank daily.

Table 5. Designed Tank Size for Population Size of 2000

S/n	Population Size	Capacity Factor	Water Use	Tank Size (litres)	Tank Dimension
1	2000	1.5	270,000	135,000	7.0 x 5.0 x 3.8

4.1 PRACTICE DESIGN FOR 4-LOG VIRUS INACTIVATION

1) The CT$_{required}$ for 4-log inactivation of virus at temperature of 15oC and pH range of 6.73 is 4 mgmimL^{-1} (EPA, 1991).

2) The CT$_{achieved}$ is shown in Table 6 for RFC range of 0.2mg/L to 0.5mg/L.

Table 6. Viral Inactivation Data for Residual Concentration Range of 0.2 to 0.5mg/L

S/n	RFC (mg/L)	CT achieved	CT required	Ratio	Virus Inactivation
1	0.2	29	4	7	Satisfactory
2	0.3	43	4	10	Satisfactory
3	0.4	59	4	14	Satisfactory
4	0.5	72	4	18	Satisfactory

3) Based on inactivation ratio for 4-Log inactivation shown in (13), this design satisfies the viral inactivation requirement.

$$\text{4-log virus inactivation} = \text{inactivation ratio} \times 4 \geq 4 \qquad (13)$$

4) The required initial concentration is shown in Table 7.

Table 7. Required Initial chlorine concentration (C_0) for residual range of 0.2 to 0.5 mg/L

S/n	Contact Time (t)	RFC (mg/L)	Chorine demand	C_0
	143	0.2	1.4	1.6
2	143	0.3	1.4	1.7
3	143	0.4	1.4	1.8
4	143	0.5	1.4	1.9

4.2 PRACTICE DESIGN FOR 3-LOG GIARDIA INACTIVATION

1) The CTrequired for 3-log inactivation of Giardia at temperature of 15oC and pH range of 6.73 for the different RFC's is shown in Table 8.

2) The CT achieved was determined using (2) and (7) indicates an inactivation ratio as satisfactory.

Table 8: 3-log Giardia Inactivation Data for Residual Concentration Range of 0.4 to 1.0 mg/L

S/n	B.F	Contact Time (t)	RFC (mg/L)	CT achieved	CT required	Ratio	Giardia Inactivation
1	0.3	143	0.4	59	59	1.0	Satisfactory
2	0.3	143	0.5	72	60	1.2	Satisfactory
3	0.3	143	0.8	114	61	1.9	Satisfactory
4	0.3	143	1.0	143	63	2.3	Satisfactory

3) The required initial dosage for the different residuals are shown in Table 9.

Table 9. Required Initial chlorine concentration (C_0) for residual range of 0.4 to 1.0 mg/L

S/n	Contact Time (t)	RFC (mg/L)	Chorine demand	C_0
1	143	0.4	1.4	1.8
2	143	0.5	1.4	1.9
3	143	0.8	1.4	2.2
4	143	1.0	1.4	2.4

4.3 DISCUSSION

For viral inactivation, high values of inactivation ratios were observed. This is indicative of high efficiency in the disinfection process. Therefore the residence time of chlorine in the water adequately provided the needed CT disinfection. The same chlorine demand was observed for both viral and gardia inactivation. This is because both have: same contact time, same log requirement, and same tank size. Therefore in order to satisfy the higher CT requirement for gardia inactivation for hydraulic contact time within the tank, higher residual concentration was observed.

Though satisfactory, additional contact time or a higher residual target should be provided for the inactivation with a ratio of 1.0 and a residual of 0.4 mg/L in Table 8. This is because at any slight lower CT, disinfection will not be satisfactory. Additional contact time can also be achieved within the pipeline before the first user, or alternatively allowing the water to stay for a longer period in the contact tank. Higher level of initial concentration was observed for gardia inactivation since it has a higher CT requirement.

5 CONCLUSION

The study has demonstrated the usefulness of chlorine demand model for the determination of initial required chlorine concentration. Chlorine demand models are generally determined through laboratory experiment.

REFERENCES

Ale, P.O., Aribisala, J.O., Awopetu, M.S. (2015). Evaluation of Yeild of Wells in Ado-Ekiti, Nigeria. IISTE Journal, Vol 7, No 11.

Army-Air Force.(1985). Water Supply, Water Storage. Technical Manual. Joint Department of Army and Air Force, USA. TM 5-813-4/AFM 88-100, Vol 4.

Casey T., Kearney, & P.,Kerr, H. (2012). The Chlorine Demand Characterization of Irish Water Supplies: Process Design Implication for Disinfection and THM Formation. CIWEM2012/CDS/WS.

Clark, R.M., Read, E.J., & Hoff, J.C. (1989). Analysis of Inactivation of Giardia Lamblia by Chlorine. Journal of Engineering Division of the ASCE. 115(1), 80-90.

Clark, R.M (1998). Chlorine Demand and TTHM Formation Kinetics: a Second-Order Model. J. Environ. Eng. 1998.124:16-24.

EPA (1991). Guidiance Manual for Compliance with the Filteration and Disinfection Requirement for Public Water System using Surface Water Sources. Environmental Protection Agency (EPA) Office of Drinking Water, Criteria and Standard Division, Science and Technology Branch, Washington, DC.

EPA (2001). Controlling Disinfection By-Products and Microbial Contamination in Drinking Water. Environmental Protection Agency (EPA) Office of Research and Development, Washington, D.C.

EPA (2011). Water Treatment Manual: Disinfection. Environmental Protection Agency (EPA) Office of Environmental Enforcement, Ireland.

Farovitch, Lorne (2016) Survival of Various Pathogenic Microorganisms in Surface Waters and Sediments in Western New York" Thesis. Rochester Institute of Technology.

Indian Standard. (1993). Code of Basic Requirement for Water Supply, Drainage and Sanitation. Public Health Engineering. IS_1172 (1993). Fourth Edition.

John, D.E & Rose, J.B (2005) Review of Factors Affecting Microbial Survival in Groundwater. Environmental Science & Technology, Vol. 39, (19), 2005, Pg 7345 to 7356.

Kohpaei, J.A and Sathasivan, A (2011) Chlorine Decay Prediction in Bulk Water Using the Parallel Second Order Model: An Analytical Solution Development. Chemical Engineering Journal. In-press.

LeChevallier, M. K., and Kwok-Keung Au. (2004) Water Treatment and Pathogen Control: Process Efficiency in Achieving Safe Drinking Water. World Health Organisation (WHO). Published by IWA Publishing, London, UK.

National Academy of Sciences (1980): Drinking Water and Health, Volume 2 Safe Drinking Water Committee, Board on Toxicology and Environmental Health Hazards, Assembly of Life Sciences. 408 pages

National Academy of Sciences. (1977) Drinking Water and Health, Volume 2. Safe Drinking Water Committee, National Academy of Sciences, Washington, D.C. 939 pp.

Netshidaulu, A.H. (2015). Impact of Chlorine and Wastewater Contact Time, Chlorine Residual and Mixing on Microorganism Inactivation. An Msc Reasearch Report for the Award of a Degree of Master of Science in Civil Engineering.

Pennsylvania Department of Environmental Protection., (2016). Module 5: Disinfection and Chlorination.. Bureau of Safe Drinking Water, Department of Environmental Protection. Waste Treatment Plant Operator Certification Training.

Rush, B. (2002). CT Disinfection Made Simple. A Presentation for the Alberta Water and Wastewater Operator's Association Annual Conference in Banff, Alberta.

USEPA. (2012). Review of Inactivation by Disinfection for SDWA Primacy Agencies.

United States Environmental Protection Agency (USEPA) Office of Groundwater and Drinking Water.

Vasconcelos, J J., Rossman, L A., Grayman WM., Boulos, PF., Clark R.M., 1997. Characterization and modeling of Chlorine Decay in distribution Systems. Journal AWWA. Volume 89 Issue 7.Pg 54 – 65.

WHO (2017). Principles and Practices of Drinking Water Chlorination. A Guide to Strengthening Chlorination Practices in Small- to Medium-Sized Water Supplies. World Health Organization (WHO) Regional Office of South East Asia.

Wiant, C. (2013). The Chlorine Residual: A Public Health Safeguard. Water Quality and Health Council. Avaliable online @ https://waterandhealth.org/healthy-pools/chlorine-residual-public-health-safeguard/. Accessed on 04/06/2018.

WRA. (2014). Fact Sheet: Log Removal Values in Waste Water Treatment. Water Research Australia (WRA) Water for the WellBeing of All Australians.