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Effect of temperature on onset of nitrification in chloraminated distribution system

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ABSTRACT

Controlling nitrification is a challenge as the causes of onset of severe nitrification in chloraminated distribution systems are not yet well identified. Biostability concept is recently introduced to define the conditions at which nitrification would onset. At biostable residual, growth rate is balanced by disinfection rate. Growth rate is a function of free ammonia present, maximum growth rate, and coefficients defining the balance are assumed constant. Although maximum growth rate and disinfection rate coefficients are known to vary with temperature, it is yet to be taken into account. Water temperature in distribution systems varies between 6 and 35°C. Optimum temperature for ammonia oxidising bacteria (AOB) is between 25 and 30°C, which makes the variation of growth rate non-exponential beyond 20°C. In this paper, how biostability curve would alter within the full practical range of practical temperature is shown, by analysing the data obtained for a bacterium that behaves similar to AOB found in distribution systems.

Keywords: Chloramine; Free ammonia; Nitrification; Biostability curve; Biostability; Temperature

1. Introduction

Giving preference to the least production of regulated disinfection by-products, especially trihalomethanes and haloacetic acids, many water utilities has switched to chloramine from chlorine as a disinfectant in drinking water distribution systems [1]. Despite such advantages, chloramine has some additional challenges in maintaining residual in long pipe lines and reservoirs with longer holding times, especially due to microbial acceleration (including that by nitrifiers through nitrification).

Nitrification is a two-step microbial process in which ammonia is initially converted to nitrite by AOB and then nitrite is converted to nitrate by nitrite oxidising bacteria (NOB). The growth rate of nitrifiers depends on ammonia concentration, temperature, pH, light, and dissolved oxygen concentration [2]. Decay of chloramine releases free ammonia, eventually resulting in suitable conditions for nitrification. Lipponen et al. [3] reported that nitrification occurs in chloraminated water systems over a pH range from 6.5 to 10.0 and at temperatures above 15°C, but it can also occur at low temperatures.

Once nitrification takes place, controlling or overcoming nitrification is very difficult even by increasing the chloramine concentration up to 8.0 mg Cl_2/L [4,5]. Under these conditions, chloramine has been found to be accelerating at a much faster rate [6] and promote bacterial regrowth [7]. Therefore it is important to identify the point at which nitrification commences.

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Despite continued research, it is still difficult to accurately predict the conditions leading to onset of nitrification. Traditionally nitrite increase is adopted as indication of onset of nitrification [3,5,6]. Sathasivan et al. [6] developed a method to identify total chlorine residual (termed critical threshold residual (CTR)) at which mild nitrifying samples switches to severely nitrifying ones. In Sydney Water distribution systems, Australia below CTR, sudden decrease of ammonia and increase of the decay rate and nitrite level were noted.

Different authors [6,8–10] concluded that chloramine residual can play a significant role along with availability of free ammonia on onset of severe nitrification in distribution systems. Woolschlager et al. [8] and Harrington et al. [11] proposed a simple formula to determine the point of biostability. Biostability concept assumes that bacterial growth can be described by Monod kinetics and bacterial inactivation can be described using Chick–Watson kinetics. According to the biostability concept, the bacterial regrowth can be prevented if the inactivation rate equals or exceeds the bacterial growth rate at each location within the distribution system.

By implementing this biostability concept, Fleming et al. [10] determined the residual below which potential for nitrification occurrence exists. This residual is termed as biostable residual concentration (BRC). This was done by balancing growth and disinfection. They used ammonia as substrate for controlling growth of AOB and dichloramine as the disinfectant. Later, citing Valentine [12], Sathasivan et al. [6] argued that dichloramine is not present in sufficient quantities to inhibit the bacteria at the operational pH of the system. Therefore, total chlorine was adopted by Sathasivan et al. [6]. The resulting equation is:

$$\mathrm{BRC} = \frac{\mu_m}{k_d} \cdot \left(\frac{\text{free ammonia}}{K_s + \text{free ammonia}} \right) \quad (1)$$

where μ_m is the maximum specific growth rate of AOB (d^{-1}); free ammonia is the sum of ammonia (NH_3) and ammonium (NH_4^+) concentrations (mg-N/L); K_s is the half saturation constant for AOB (mg/L); k_d is the rate constant for inactivation of AOB by disinfectant ($L.d^{-1}\,mg\,Cl_2^{-1}$); BRC is measured as total chlorine concentration (mg Cl_2/L). Biostability curve is drawn as a curve for free ammonia vs. BRC. Fleming et al. [10] obtained μ_m/k_d and K_s values of 2 mg Cl_2/L and 0.5 mg-N/L for a pilot scale system. Sathasivan et al. [6] obtained the same μ_m/k_d, but a different K_s value (0.18 mg-N/L). Fleming et al. [13] analysed full scale system data and proposed different μ_m/k_d and K_s values than that was obtained by Sathasivan et al. [6] in mildly nitrifying bulk water samples from Sydney Water Distribution or pilot scale systems. They explained the difference as different microbiological species present in different systems and as difficulty in obtaining literature data on bacterium present in the chloraminated systems. However, to explain why different parameters are obtained in different systems most important conditions that define biostabiltiy concept need to be considered before assigning the variation to bacterial diversity, such as temperature.

It is known that temperature highly affects nitrification in wastewater treatment plant. In order to decide whether nitrification would be affected by temperature, it is necessary to know the effects of temperature on growth rate as well as inactivation/inhibition rate of nitrifiers. Traditionally growth rate is modelled using exponential function, although a better description was provided by Ratowsky et al. [14] for sub-optimal temperature range. In water distribution systems, operating temperature range is 6–35°C. In drinking water systems, various authors [4, 14, 15] reported that the optimum temperature for nitrifier growth is 25–30°C. The maximum temperature experienced by some utilities is about 5°C higher than optimal temperature. For example, water conduits in Goldfield and Agricultural Water Supply System of Western Australia experience as high as 40°C. Therefore, it is necessary to understand how those parameters would affect beyond sub-optimal temperature is also needed.

The purpose of the paper is to show how temperature would impact the biostability parameters in the region of interest, i.e. 6–35°C. Literature data obtained for growth rate of psychrophilic bacteria, which behaves somewhat similar to AOBs found in distribution systems, is used. Assuming that this behaviour also holds true for AOBs, and by assuming k_d varies with temperature in the way it is described in the literature, possible variability of μ_m/k_d and its implications for operation and modelling is discussed, although a proper experimental data is needed to validate the results for AOB.

2. Materials and methods

2.1. Determination of growth rate variation with temperature

For this study, data were collected from Johnson et al. [16] for full practical range and used for the development of the proposed method. The general characteristics of the samples used for the method is described in Johnson et al. [16]. The curve of growth rate constant versus water temperature as drawn in Fig. 1 for the collected data from the literature [16] shows the effects of temperature on growth rate of *Aerobacter aerogenes*.

2.2. Brief description of the experiment

Culture containing strains of *Aerobacter aerogenes* were incubated at 35, 30, 20, 15, 10, 5, and 0°C. At suitable intervals, samples were removed from the culture for bacteriological analyses. Standard plate count method was followed for viable counting, where plates were incubated at 20°C for 5 days before counting. Full descrip-

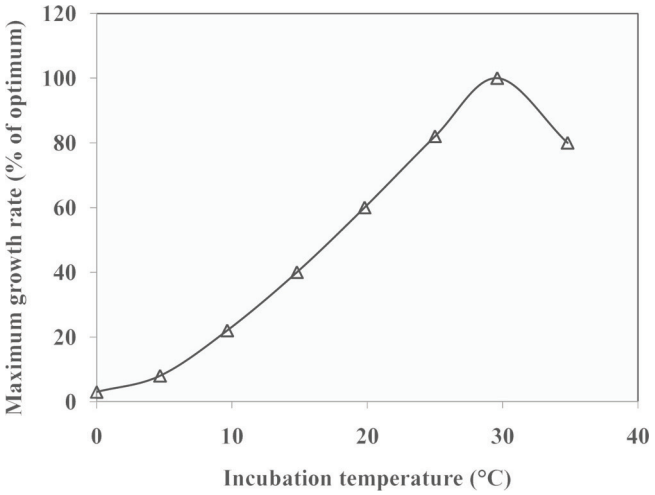

Fig. 1. Variation of maximum growth rate of *Aerobacter aerogenes* with temperature.

tion of the experimental procedure is detailed in Greene and Jezeski [17].

2.3 Determination of inactivation rate constant variation with temperature

The effects of temperature on inactivation rate constant k_d due to disinfection can be modelled using the Arrhenius equation [18].

$$k_{d,T} = k_{d,20}.\exp\left[-\frac{E}{R}\left(\frac{1}{273+T}-\frac{1}{273+20}\right)\right] \quad (2)$$

where $k_{d,T}$ and $k_{d,20}$ are the inactivation rate constant of bacteria at temperature T (°C) and 20°C respectively, E is the activation energy (J/mole) and R is the universal gas constant (8.3144 J/mole.K). Fair et al. [19] reported the activation energy for chloramine at 20°C is 50,250 J/mole for pH 7 and 58,630 J/mole for pH 8.5. By interpolation and simplifying, E/R value can be considered as 6500 K^{-1}.

2.4. Determination of μ_m/k_d variation with temperature

To determine the variation of μ_m/k_d with temperature, first the value was set at 2.0 mg Cl_2/L at 20°C, as this was the value obtained by various authors [6,10,11]. Using the percentage growth $\mu_{m,20}$ at 20°C (60% of full growth rate), $k_{d,20}$ value is estimated as same as the value of 30% of full growth rate of the bacteria. Using Eq. (2), value of k_d at 0, 5, 10, 15, 25, 30 and 35°C can be estimated, if E/R value is known. Using Fig. 1, value of μ_m at different temperatures can be evaluated. If the relative relationship is used throughout then possible variation of μ_m/k_d with temperature can be evaluated.

3. Results and discussion

3.1. Effect of temperature on μ_m/k_d value

The relation of free ammonia with BRC can be explained by Eq. (1), where μ_m/k_d was always chosen as 2.0 mg-Cl_2/L at 20°C [6,10,11]. In Fig. 1, it has been shown that temperature greatly governs the growth rate, μ_m. In order to understand the effect of temperature on μ_m/k_d, they were estimated for different temperatures following the procedure described in section 2.4. The results are plotted in Fig. 2. It is clear from Fig. 2 that μ_m/k_d value varies greatly with temperature.

3.2. Implications for residual management in distribution system

Fig. 2 can be used to understand why certain behaviour happens when temperature changes.

In Sydney Water distribution system, water temperature variation does not affect biostability parameters heavily as can be noted in Figs. 3 and 4. In Fig. 3 one can see the maximum μ_m/k_d is 2.1 mg Cl_2/L at 17°C. The minimum value occurs at 13°C, the value is 1.8 mg Cl_2/L. In Fig. 4, it can be seen that both curves for 13°C and 17°C curves are closer to each other.

On the contrary, water temperature variation had a great impact on biostability parameters in Goldfield and Agricultural Water Supply System. The maximum and minimum of μ_m/k_d for this system is 2.1 and 0.9 mg Cl_2/L respectively, implying that this water utility needs to consider the temperature effect much more seriously. The same conclusion can be drawn from Fig. 4.

Fig. 4 shows BRC curves having different μ_m/k_d values obtained from Fig. 2 for different temperatures where BRC is calculated according to Eq. (1), using the same typical parameters (total chlorine, free ammonia and K_s). As per biostability concept, the point P must not show any sign of nitrification and the point S should for all the

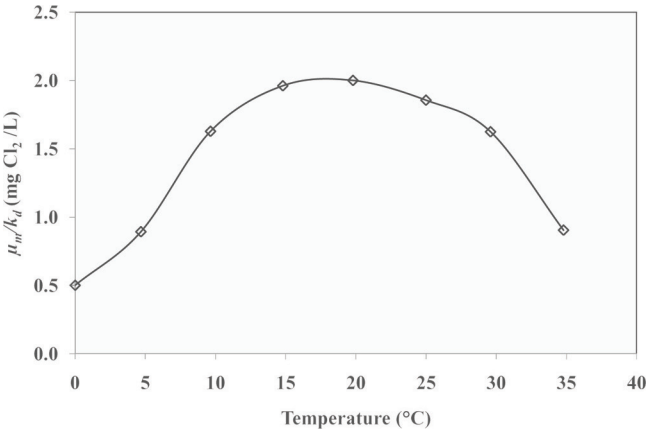

Fig. 2. Description of μ_m/k_d as a function of temperature.

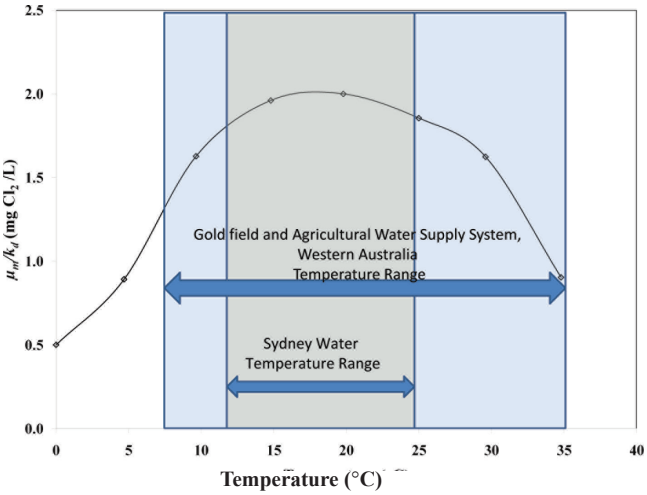

Fig. 3. Biostablity coefficient (μ_m/k_d) variation and operational temperature range of some Australian water Supply Systems.

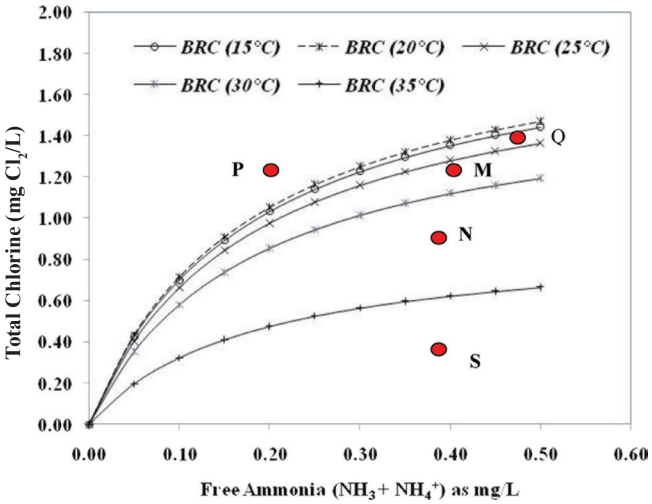

Fig. 4. BRC curves for different μ_m/k_d values at different temperatures.

values of μ_m/k_d due to temperature variations. The points Q, M and N are supposed to show the sign of nitrification at temperature above 15°C but the point Q would not at temperature 25°C and is likely to show nitrification when the temperature is 20°C. Similar phenonema would occur for the points M and N.

The above discussion leads to a conclusion that temperature more than 17°C is actually controls microorganisms better. From Figs. 2 or 3, it can be seen that as temperature increases from 17°C, μ_m/k_d value actually decreases, implying that despite the noticing of onset of nitrification in this range chloramine becomes more effective in controlling nitrification. This is because increased temperature decreases the chloramine residual and increases the free ammonia, it eventually works against advantage obtained from decreased μ_m/k_d.

Therefore, prediction of nitrification onset by biostability concept is very critical because of μ_m/k_d value variation with temperature. Such consistent definition of parameters will allow systems to more confidently use the biostability concept for efficient nitrification control measures.

4. Conclusion

Knowledge of the temperature effects on bacterial growth rate and inactivation rate can be used as an early warning of nitrification in different seasons of the year in the distribution system. As the finding of the study gives a novel approach of calculating μ_m/k_d in different temperatures, the water utilities can take advance initiative for overcoming nitrification with correct BRC values. The major conclusions made from the analysis are presented below:

- The μ_m value increases with the increase of temperature up to a certain temperature and then start to decrease, whereas k_d value increases with increasing temperature. Therefore, the μ_m/k_d strongly varies with temperature with maximum happening at around 20°C.

Symbols

E — Activation energy, J/mole
k_d — Rate constant for inactivation of AOB by disinfectant, L.d^{-1} mg Cl_2^{-1}
K_s — Half saturation constant for AOB, mg/L
R — Universal gas constant, J/mole.K
μ_m — Maximum specific growth rate of AOB, d^{-1}
$\mu_{m,T}$ — Maximum growth rate constant, d^{-1} at temperature T, °C

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