Abstract

In this study, a typical chlorine control application called KhloCheq has been developed. KhloCheq seeks to control chlorine concentration at the disinfection stage of water and wastewater treatment. The application was developed using Visual Basic programming language. The application can operate in both manual and automatic modes during chlorine disinfection. In the manual mode, KhloCheq alerts an operator by sounding an alarm and suggesting the percentage by which chlorine supply rate should be increased or decreased when the measured value is not equal to the set point. In the automatic mode, the application automatically adjusts the chlorine concentration to the desired value with the help of chlorine analytical transmitter, controller and final controlling element. The application also uses feedback and feed-forward process control mechanisms to adjust chlorine concentration to the set point. KhloCheq can be very useful for disinfection in water and wastewater treatment facilities when the right analytical sensor is used. This will ensure that the right amount of chlorine injection is used for disinfection to avoid any adverse impact on the environment.

Keywords: Chlorine; Simulation; KhloCheq; Visual Basic Programming; Disinfection

1 Introduction

In wastewater treatment, chlorine is injected either as a gas or liquid into the feed at the disinfection stage to kill microorganisms before it is released into the environment (Morris, 1971). Chlorine is also added to wastewater in the sedimentation and filtration tanks to prevent the formation and growth of microbes (Kumar, 2015). The right amount of chlorine is needed to kill pathogens, remove tastes and odours, and eliminate unwanted nitrogen compounds in water (Morris, 1986; Burlingame et al., 1992; Gottschalk et al., 2000; Lugube, 2003; Sadiq and Rodriguez, 2004). Excessive chlorine in water could cause cancer by reacting with some organic substances in the water (Becher, 1999; Gopal et al., 2007), corrode the distribution pipes and poison certain useful living organisms in the ecosystem (Betts and Wilson, 1966; Kulphaldt, 2008). Insufficient chlorine injection also results in the distribution or release of unwholesome water into the environment.

Generally, the recommended concentrations of residual chlorine for disinfection of treated water are between the range of 0.5 and 1.0 mg/L after a contact time not less than thirty (30) minutes (Brungs, 1973). This ‘residual’ chlorine remains in the water to serve as a safety measure against microorganisms and pathogens that could be present in the effluent pipes (Wiant, 2013). According to the United States Environmental Protection Agency (US EPA), the most common dosage for chlorination is between 5-20 mg/L and the use of chlorine control applications at the disinfection stage can be very efficient in meeting the requirement standards of residual chlorine (Kulphaldt, 2008).

Due to the effects of chlorine on the environment, most water treatment facilities use dechlorination methods such as the use of sodium dioxide, sodium bisulphate and ascorbic acid to remove excess chlorine in order to meet the regulatory residual chlorine standards (Snowden-Swan et al., 1998). The dechlorination methods can increase the cost of water treatment and introduce other wastes and by-products. Thus to ensure that the set point (or regulatory residual chlorine) is achieved, a software is needed to monitor and control the concentration of chlorine in the water. This software should be able to alert the operator and adjust the chlorine supply if the measured concentration is less or more than the set point and release the water into the environment if the set point is achieved. Water treatment facilities in Ghana however, do not have any software to control disinfection.

This work seeks to simulate a disinfection system and develop an application called KhloCheq to control the chlorine concentration in water and waste water treatment system, by adopting and modifying the Process and Instrumentation Diagram (P&ID) shown in Fig. 1, according to Kulphaldt (2008). KhloCheq was developed using Visual Basic (VB) programming language for the water treatment facilities in Ghana to reduce the work load of water treatment officers and reduce the cost of water disinfection.
In the P&ID (Fig. 1), chlorine gas coming through the control valve mixes with the incoming water (influent) through turbulent action in a mixer. After this, the water with chlorine flows into the contact chamber and has time to disinfect before exiting out to the environment. Analytical Transmitter measures the residual chlorine concentration and sends the equivalent electrical signal (4-20 mA) to the Analytical Indicating Controller (AIC) which also compares the signal to the set point (SP) and sends a control signal (4-20 mA) to the final controlling element (Motor-operated control valve) to either increase or reduce the flow of chlorine into the system. This system serves as the basis of the operation of KhloCheq.

![Fig.1. P&ID of Chlorine Disinfection System (Kuphaldt, 2008)](image)

### 1.1 Disinfection

Disinfection is the process of killing/destroying harmful microorganisms (such as disease-causing bacteria or pathogens) in water with chemicals or substances called disinfectants. It is mostly the last process in water treatment and is done before the treated water is released into the environment or distributed to households. A disinfection process should have the following qualities (Anon, 2002):

(i) It should not result in an increase in the toxicity of the water.

(ii) It should be reliable, cost effective and not cause more risks to human health or the environment as a result of the transport, storage and handling of the chemicals used for disinfection.

(iii) It should reduce the amount of bacteria and other living organisms in order to make the quality of the water meet the statutory regulation limits of water.

### 1.2 Methods of Disinfection

Methods of disinfection can be classified as chemical, physical or biological. The chemical methods include ozonation and chlorination while the physical methods comprise ultraviolet radiation, microfiltration, etc.; the biological method includes the use of detention lagoons (Anon, 2002; Wang et al., 2005). As far as this work is concerned, the method of chlorination is discussed.

#### Chlorination

This is the method of disinfection in which chlorine is used to disinfect water in either the gaseous form (Cl₂), hypochlorite salts form such as sodium hypochlorite (NaOCl) and calcium hypochlorite [Ca(OCl)]₂ or chlorine dioxide form (ClO₂). (Wang et al., 2004; Wang et al., 2005) The use of chlorine gas (Cl₂) has been found by literature to be inexpensive and an efficient bacterial disinfectant with a shorter contact time than other options. The main disadvantages of Cl₂ are its safety concerns and its ineffectiveness against some microbes such as Cryptosporidium (Snowden-Swan et al., 1998). The use of chlorine-based options for disinfection (Chlorination) have been known to be associated with cancer and other health effects, and as a result, they have strict regulatory guidelines.

Cl₂ is absorbed and distributed in raw water to form hypochlorous acid (HOCI) which kills the target microorganisms in the water. The chemical equation for the use of Cl₂ is shown in Eq. (1):

\[
\text{Cl}_2 + \text{H}_2\text{O} \rightarrow \text{HOCI} + \text{HCl}
\]  

Sodium hypochlorite (NaOCl or liquid chlorine) has similar chemical reaction with water and disinfection efficiency as chlorine gas but it is safer and more expensive than Cl₂. Calcium hypochlorite [Ca(OCl)]₂ is also safer than Cl₂ and more stable than both NaOCl and Cl₂ because of its solid nature which makes it relatively easier to handle. It is relatively expensive and can react slowly with moisture in the atmosphere to form chlorine gas, thus, Ca(OCl)₂ must be stored in air-tight containers (Snowden-Swan et al., 1998).

Chlorine dioxide is known to be a more effective chlorine based disinfection method than chlorine gas and it produces less Trihalomethane (THM) by-products (Singer, 1993). Despite its effectiveness, chlorine dioxide can be very difficult to handle because it becomes explosive at levels above 10% in air and it is more expensive than chlorine gas. Chloramine can also be used to disinfect water. Chloramine is a chemical generated from the addition of chlorine (gas or hypochlorite) to ammonia-based water or ammonia to chlorine-based water (Brungs, 1973). Its disinfection efficiency is not as strong as chlorine gas but is known to be relatively stable. Due to its relatively low Oxidation-Reduction Potential (ORP), it does not produce disinfection by-products that are above regulatory limits (Snowden-Swan et al., 1998).
**Chlorine Demand Test:** It is a simple test done to determine the amount of concentrated chlorine solution (mother solution) that would be needed to produce a specific residual chlorine concentration in disinfected water after the required contact time (Rottier and Ince, 2003). The apparatus used for the test include measuring jar, four to six (4-6) non-metallic vessels, syringe without needle, watch and pooltester.

The vessels are filled with a known volume of the raw water (equal amounts of the raw water). Varying amounts of the mother solution are added to each vessel of water with the syringe (Example: 0.5 mL, 1 mL, 1.5 mL, etc.). The water and chlorine are mixed and allowed a contact time of about thirty (30) minutes (Rottier and Ince, 2003).

After the contact time, the residual chlorine concentration of each vessel is tested with the pooltester. The vessel of water that gives the desired residual chlorine concentration gives the idea of the chlorine demand of the water. For a batch of water, Eq. (2) is used to determine the amount of chlorine that would be needed to achieve the desired residual chlorine concentration and Eq. (3) is used to determine the amount of chlorine to be supplied per second (rate) to a continuous flow system to disinfect the water (Rottier and Ince, 2003).

\[ M_{\text{bat}} = \left( \frac{\text{Vol}_{\text{bat}}}{\text{Vol}_{\text{test}}} \right) \times M_{\text{test}} \]  

(2)

where \( M_{\text{bat}} \) is the amount of chlorine required to disinfect the batch of raw water (mL), \( \text{Vol}_{\text{bat}} \) is the volume of the batch water (L), \( \text{Vol}_{\text{test}} \) is the volume of water that was used in the test (L) and \( M_{\text{test}} \) is the amount of mother solution that produced the desired residual chlorine concentration in the test (mL).

\[ R_{\text{Ms}} = \left( \frac{\text{Flow}_{\text{sup}}}{\text{Vol}_{\text{test}}} \right) \times M_{\text{test}} \]  

(3)

where \( R_{\text{Ms}} \) is the rate at which the mother (chlorine) solution would be added to the raw water (mL/s) and \( \text{Flow}_{\text{sup}} \) is the flow of the raw water into the system (L/s).

2 Design and Testing of Khlocheq

2.1 Visit to Water Treatment Facilities

Ghana Water Company (GWC)-Bonsa Operations and Veolia Wastewater Treatment Facility at Anglogold Ashanti Iduapriem Limited (AAIL) were visited to interview the water treatment officers about the disinfection process, the whole water treatment process and how chlorination is controlled. These trips were made in order to learn about the disinfection and water treatment processes to confirm the need for a chlorine control application in disinfection.

At Bonsa, it was revealed that the company has no chlorine control application to control chlorination and thus the laboratory technician takes samples every hour to check the residual chlorine concentration in order to ensure that the desired residual chlorine concentration is achieved. Lime is added to the water to adjust the pH of the water at the disinfection stage. The hypochlorous acid (HOCl) shown in Eq. 1 dissociates further depending on the pH of the solution (Morris, 1966). The higher the pH, the more it will react as shown in Eq. 4:

\[ \text{HOCl} \rightarrow \text{OCl}^- + \text{H}^+ \]  

(4)

The more hydrogen ions present, the lower the pH. At pH of 7 (neutral pH), almost 80% of the chlorine is in the form of hypochlorous acid (most effective disinfecting form); the reminder exists in the less effective disinfecting form hypochlorite ion (OCl\(^-\)) (Morris, 1966; Deborde and Von Gunten, 2008; Gopal et al., 2007; Wang et al., 2005).

At pH 8 and above, nearly 80% of the chlorine is present as the less effective hypochlorite ion (Wang et al., 2005). Hence lime is carefully added to adjust the pH of the water to fall within the range of 6.5-8.5 (approximately 7.5 for effective disinfection), which is the regulatory pH range for drinking water. Fig. 2 shows the chlorination tank at Bonsa and Fig. 3 shows the chlorine supply pipe (Left pipe), influent pipe (Centre) and lime supply pipe (Right) in the chlorination tank.

![Fig. 2 Chlorination Tank at GWC Bonsa](image-url)
Fig. 3 Influent, Chlorine and Lime supply in the Chlorination Tank

At Veolia, it was clearly stated that the treatment process does not include disinfection because the facility treats industrial wastewater. It was explained that the industrial wastewater does not contain bacteria and algae from their study and analysis. The respondent however made mention of the fact that the facility had to resort to the trial and error method in 2015 when the need arose for the facility to disinfect the water as a result of the presence of algae in the wastewater. This further confirmed the need for a chlorine control application in water disinfection.

2.2 Purpose and Equations of KhloCheq

The main purpose of KhloCheq is to measure residual chlorine concentration of treated water and ensure that the desired concentration is achieved to avoid the associated effects of improper or inefficient chlorination. The operations of the application depend on basic interpolation and Eqs. (3), (5) and (6);

(i) Chlorine Supply Rate (Rottier and Ince, 2003): Eq. (3) makes use of the values used in test to determine the chlorine demand of the water in order to make predictions as to the amount of chlorine that will be required every second to achieve the set point.

$$\text{MV} = \left( \frac{M_s - \text{LRV}_m}{\text{Span}_m} \right) \times (\text{Span}_m) + \text{LRV}_m$$  \hspace{1cm} (5)

(ii) Transmitter-Transducer - Measured Value Conversion (Kuphaldt, 2008): Eq. (5) is used by the transducer component to convert the measured signal (in milli-amperes) of the transmitter to concentration (in mg/L) in order for it to be compared to the set point (mg/L).

Where, MV is measured value, M_s is measured signal, LRV_m is lower range value of the transmitter signal, Span_m is span of transmitter signal, Span_m= Span of measurement and LRV_m is lower range value of measurement

(iii) Error (Transmitter - Transducer - Chlorine Valve). When the measured value is not equal to the set point (MV< or >SP) then the difference between these values are calculated using Eq. (6) below. In the automatic mode, the valve is adjusted with this equation, but in the manual mode, the system suggests to the operator to adjust the valve by the percentage obtained from Eq. (6).

$$\text{Valve Correction} = |(\text{SP} - \text{MV}) \times \text{(Rate)}|$$  \hspace{1cm} (6)

where SP is set point, MV is measured value and Rate is rate at which chlorine is supplied to the system

2.3 Design of KhloCheq

The interface of KhloCheq was designed using common Visual Basic (VB) controls such as textboxes, labels, track bar and radio buttons in the simulation section of the interface to show the flow of the water, the percentage by which the chlorine valve is opened and whether the effluent valve is opened or closed to release or prevent the release of treated water into the environment or receiving streams. The user input section was also designed using VB controls such as;

(i) Buttons to start, stop, continue and reset the disinfection process.

(ii) Labels to inform the user about the system parts.

(iii) Radio buttons to select the mode of operation of the system.

(iv) Textboxes to accept parameters of the system from the user

2.4 Coding

The codes were written with Visual Basic (Visual Studio 2013). It is made up of many declaration statements, conditional statements (IF-then statements), comparison of parameters and conversion of parameters in order to ensure effective operation of the software.

About five hundred (500) lines of programming codes were used to build the application’s main interface and forty-five (45) lines of codes went into the development of the splash screen. The codes for the application are shown in Appendix A and that of the splash screen are shown in the
Fig. 4. Flowchart of KhloCheq

2.5 Testing of KhloCheq

KhloCheq was run on computers to test how it runs on some operating systems. The application functions and works well on Windows 7, 8 and 10 but does not run on Apple Macintosh operating systems and Android operating system.

3 Results and Discussion

3.1 Operation of KhloCheq

KhloCheq (Chlorine Checking Application) was developed by modifying and simulating the Process and Instrument Diagram (P&ID) of a disinfection system showed in Fig. 1. KhloCheq operates in both manual and automatic modes using both feed-forward and feedback mechanisms. The feed-forward mechanism (which occurs right when water starts flowing into the mixer) tries to prevent the difference between the set point and the measured value called error by supplying the right amount of chlorine initially to the mixer based on the mathematical expression of the chlorine demand test and the amount (volume) of raw water entering the system per second (Eq. 3). External factors such as temperature, and particles in the system pipes may however increase or decrease the chlorine demand of the water and this can introduce error into the system. The feedback mechanism (which occurs in the contact chamber after the analytical transmitter measures the residual chlorine concentration) then ensures that the error which was not corrected by the feed-forward system is corrected in order to achieve the set point. The modes of operation of KhloCheq are discussed in the following paragraph.

In the manual mode, KhloCheq has been designed to measure the chlorine concentration in the contact chamber, trigger an alarm to alert the operator and suggest the percentage by which the chlorine valve has to be adjusted to achieve the set point when the measured value is not equal to (Greater or less than) the set point concentration. The operator can then adjust the chlorine supply to achieve the required chlorine concentration for disinfection before opening the effluent valve without any adverse effect. In the automatic mode, KhloCheq has been designed to measure the chlorine concentration in the contact chamber. It compares the measured value to the set point and adjusts the chlorine control valve automatically depending on the measured value with the aid of the Analytical Transmitter (AT) and Analytical Indicating Controller (AIC).

3.2 Interface of KhloCheq

Before the main interface of KhloCheq appears, there is a splash screen which shows the information of KhloCheq while the application loads. The splash screen of KhloCheq is shown in Fig. 5. KhloCheq has a simple and interactive interface which is made up of the user controls and a simulation section. The simulation section mainly consists of controls to show the flow of the raw and disinfected water in the system and radio buttons to allow/restrict the flow of water in the system. It also has user controls which accept inputs or actions from users to function. Fig. 6 shows the Graphical User Interface (GUI) of KhloCheq before it starts operating or it is started.

Fig. 5. The Splash Screen of KhloCheq
3.2.1 User Controls

**Buttons**

The buttons in this software are the Start, Stop, Continue, Reset and Accept buttons. When clicked, the Start button starts the flow of the feed through the influent valve, the stop button stops the flow of water in the simulation section, the continue button makes the fluid in the simulation section resume its flow and operation and the reset button clears the pipes in the simulation section. The accept button in the Analytical Indicating Controller also serves as the input option for the sensor’s output.

**Radio Buttons**

The software makes use of radio buttons. Radio buttons are used to select the mode of operation (Automatic or manual) and to show the state of the valve because there is no valve object in the visual basic toolbox.

**Textbox**

The software also has textboxes to take the inputs of the user such as the set point and measured value. These textboxes were programmed to reject alphabets and other non-numeric characters to ensure efficient operation and also notify the user when the set limits for the parameters are exceeded.

3.2.2 Conditional Interface of KhloCheq

KhloCheq was run with constant values to show how the application operates in both modes and the various conditions (Measured value <, > or = Set point). The values used are as follows:

- Set point: 5.63 mg/L
- Flow rate: 8 L/s
- Test Volume: 10 L
- Chlorine Amount: 7 Ml

These parameters initially would cause the chlorine gas supply valve to open by 28%. Therefore, the various conditions and how they change or maintain the valve supply rate to achieve the set point are presented in the subsequent sections and shown in Figs. 7 – 10.

**Automatic Mode**

In the automatic mode, the application automatically opens the outlet valve to allow water out of the system when the measured value is equal to set point as shown in Fig. 7. The application also automatically changes the chlorine valve to a percentage that would change the chlorine concentration in order to achieve the set point. For the parameters entered above, assuming the measured value is 2.81 mg/L (Signal is 7 mA), the valve would be adjusted from 28% to 47% open in order to increase the amount of chlorine added per second and achieve the set point as shown in Fig. 8.
Fig. 7 When Measured Value is Equal to Set Point (Automatic mode)

Fig. 8 When Measured Value is less than Set Point (Automatic mode)
For the last condition in the automatic mode, a higher measured value (8.44 mg/L from a 13 mA signal) was used in order to show what the application does when the measured value is greater than the set point. The valve percentage automatically changed from 28% to 9% in order to reduce the rate of chlorine supply so that the set point would be achieved and the water can be allowed to flow out of the system as illustrated in Fig. 9.

**Manual Mode**

The manual mode notifies the operator to open the effluent valve to discharge water when the set point is equal to the measured value. It also notifies the operator when the measured value is not equal to the set point by sounding an alarm and reading out the percentage by which the operator should adjust the valve in order to achieve the set point. It gives the user the option of accepting that suggestion. By clicking on the Apply button in the Analytical Indicating Controller (AIC), the valve percentage would change to the suggested valve percentage in order to achieve the set point. Fig. 10 shows the interface after the user opens the effluent valve to allow treated water out of the system.

3.2.3 Limitations of KhloCheq
The support of Environmental and Safety Engineering Department, University of Mines and Technology, Tarkwa is highly acknowledged. Ghana Water Company (GWC)-Bonsa operations and Veolia wastewater treatment facility at Anglogold Ashanti Iduapriem Limited (AAIL) are also greatly thanked for the tremendous help about the disinfection and water treatment processes. Emmanuel Asante, a former student (University of Mines and Technology, Mathematics Department) is also greatly acknowledged for his tremendous help in the VB code writings.

References


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VB only has discrete track bars and as a result of this the valve output only shows integers by rounding up decimals. The application also works for the following range of parameters;

(i) Set point: 0.2 - 15 mg/L
(ii) Measured Value: 0 – 15 mg/L
(iii) Amount of Chlorine used in test to achieve the set point: ≤ 10 mL
(iv) Volume of water used in test: 10 Litres
(v) Flow rate: 0.1 - 20 L/second.

4 Conclusions and Recommendations

A typical chlorine control application called KhloCheq has been developed using Visual Basic (VB) for the purpose of aiding the chlorine disinfection in water and wastewater treatment. It is an interactive software that measures, alerts and/ or controls chlorine concentration at the disinfection stage using both feed-forward and feedback mechanisms. The software operates in two (2) modes; automatic and manual modes. In the manual mode, the application alerts an operator by sounding an alarm and suggesting the percentage by which chlorine supply rate should be increased or decreased when the measured value is not equal to the set point. In the automatic mode, the application automatically adjusts the chlorine concentration to the desired value with the help of chlorine analytical transmitter and controller. The software can be quite useful to water treatment facilities for disinfection when the right analytical sensor, signals and controller are used.

The recommendations of this study are the following:

(i) A chlorine control system should be developed using other programming languages such as C++, C#, Java, etc. to eliminate the limitations of KhloCheq that resulted from the use of Visual Basic.
(ii) Water treatment facilities should ensure the use of chlorine control applications softwares with appropriate sensors in a closed loop to ensure effective chlorine monitoring and control at the disinfection stage and avoid excessive cost of disinfection due to over-chlorination and the associated dechlorination costs.
(iii) The output of KhloCheq should be controlled by standard algorithms in Process Control such as the Proportional-Integral-Derivative (PID) algorithm in controller to manage and eradicate errors effectively.

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