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Liquid, Gas Chlorine and On-site Generation in Drinking Water Facilities Design Consideration and Comparison of Operating Costs

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Abstract

Chlorine the most widely used disinfectant worldwide and the technological advances develop alternatives system that allowed efficient use of chlorine in water disinfection. In our country, although sodium hypochlorite and gas chlorination is usually used as disinfection for water treatment plants, on-site chlorine generators have begun to be recently used. Sodium hypochlorite and gas chlorination is to find the most common applications in water treatment plants. In this study, information about mechanical equipment, working principle and storage conditions of the sodium hypochlorite, gas chlorination and on-site sodium chlorine generation is given. Also, initial investment cost and operating costs are compared with the costs obtained from the companies. For this purpose, cost analysis is done on two different flows, considering only the storage chlorination. Cost comparison show that the initial investment cost of site-generated sodium hypochlorite system is found to be higher than other chlorination systems while operation cost is lower.

Anahtar Kelimeler: Drinking water, Disinfection, On-site generation, Chlorine gas, Sodium hypochlorite

İçme Suyu Tesislerinde Sıvı, Gaz Klorlama ve Yerinde Klor Üretimi Tasarım Esasları ve İşletme Maliyetlerinin Karşılaştırılması

Öz

Klor dünyada en yaygın olarak kullanılan dezenfektandır ve teknolojik gelişmeler suyun dezenfeksiyonunda klorun etkili kullanımına izin veren alternatif sistemleri ortaya çıkarmıştır. Ülkemizde sodyum hipoklorit ve gaz klor su dağıtım sistemleri için dezenfeksiyon olarak yaygın kullanılmasına rağmen, yerinde sodyum hipklorit üretimi son zamanlarda kullanılmaya başlanmıştır. Sodyum hipoklorit ve gaz klorlama su dağıtım sistemlerinde yaygın uygulamaları bulmaktadır. Bu çalışmada, sodyum hipoklorit, gaz klor ve yerinde sodyum hipoklorit üretim sistemlerinin mekanik ekipmanları, çalışma prensipleri ve depolanma koşulları hakkında bilgi verilmiştir. Ayrıca ilk yatırım maliyetleri ve bu sistemlerin kullanılması durumunda harcanacak işletme giderlerinin karşılaştırılması firmalardan temin edilen fiyatlar ile yapılmıştır. Bu amaçla maliyet analizleri yalnızca depoda klorlama yapılması durumu dikkate alınarak iki farklı debi için yapılmıştır. Maliyet karşılaştırması yerinde sodyum hipoklorit üretim sisteminin ilk yatırım maliyeti diğer klorlama sistemlerine göre yüksek olmasına rağmen işletme maliyeti daha düşük olduğu göstermiştir.

Keywords: İçme suyu, Dezenfeksiyon, Yerinde klor üretimi, Gaz klor, Sodyum hipoklorit

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1. INTRODUCTION

Today, the disinfectants that are widely used in the treatment of drinking water are free chlorine, chloramines, chlorine dioxide, ozone and ultraviolet radiation (UV). Chlorine is the most commonly used disinfectant since it creates an efficient and lasting effect when it is applied at a sufficient dosage in low concentrations, and also it is cheap [1,2].

As shown in Figure 1, mostly free chlorine was used as disinfectant in water in 1978; including 91% of the disinfectants used is chlorine gas and 7% of them is sodium hypochlorite (bleach). In 2007, 63% of them was used as chlorine gas and nearly 40% of them was used as bulk liquid or on-site production of sodium hypochlorite. Since chlorine gas is highly toxic, a shift from chlorine gas towards hypochlorite has occurred due to safety and security reasons [2].

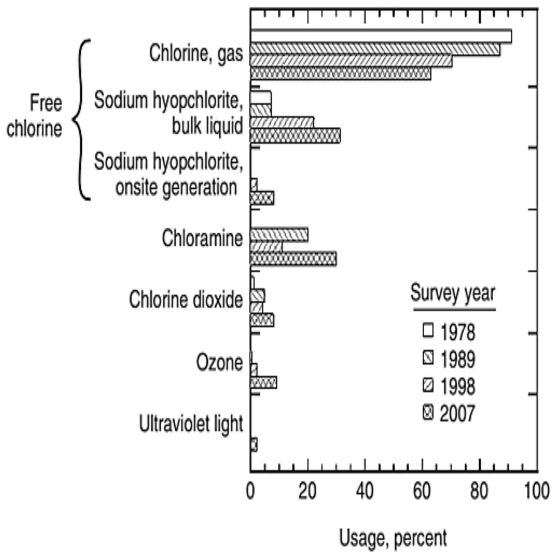

Figure 1. The chemicals used for disinfection [1]

The selection of the chlorine systems depends on the answers given to the following questions:

➢ How much disinfectant is necessary?

➢ How easy the product can be obtained?

➢ Is there the capacity necessary for use, operation and equipment maintenance?

➢ Are there the resources necessary for protection of the workers against exposure to health risks during storage and contact of hands with the material?

➢ Are the economical and financial capacities available to meet the investment, operation and maintenance costs?

In order to answer these questions, it is necessary first to identify the target area and set forth the technical, economical and social situations accordingly. The amount of disinfectant that will be required will be dependent on the flow rate of water to be reclaimed. The required dose will be determined in accordance with the water quality and drinking water standards in the country [3].

Gas Chlorination System

Disinfection with chlorine gas is cheap and the most widely used technology in the world [3]. Chlorine produced as gas liquefied under pressure is usually stored and shipped in 45-68 kg cylinders, or 10 ton container or tanks [5,6]. Chlorine is only slightly soluble in water; its maximum solubility is approximately 1% (10,000 ppm [mg/L]) at 9.6°C. Since the vapor pressure of chlorine increases as the temperature increases, its solubility reduces [6]. Chlorine gas and water react to form hypochlorous acid (HOCl) and hydrochloric acid (HCl). Hypochlorous acid (HOCl) is decomposed to hypochlorite ion (OCl^-) and hydrogen ion (H^+) according to the following reactions, respectively [7].

$$Cl_2 + H_2O \leftrightarrow HOCl + HCl \qquad (1)$$

Chloride — Hypochlorous Acid — Hypochlorite Acid

$$HOCl \leftrightarrow H^+ + OCl^- \qquad (2)$$

Hypochlorous Acid — Hydrogen Ion — Hypochlorite Ion

Reactions are reversible and depend on pH:

• Between pH 3.5 and 5.5, HOCl is predominant.

• Between approximately pH 5.5 and 9.5, both HOCl and OCl^{-} types are available in various ratios.

• Above pH 8, OCl^{-} is predominant [7].

The most widely used one among the chlorine gas feeders is vacuum system. Vacuum system equipment consists of gas cylinder, rotameter (feed rate indicator), flow regulator and injector [3]. In the operation principle of the system; chlorine gas is sucked from the pressure vessel and the chlorinator that is operated in case of vacuum is reduced to a value lower than the ambient pressure by means of a standard vacuum regulator combined with pressure relief valve. Gas is measured by means of an adjustable orifice. The gas flow rate indicated by a flow meter is controlled by an adjustable orifice area. Vacuum regulating valve reduces fluctuations and provides smooth operation. Vacuum relief valve prevents excessive vacuum in the equipment. Control of gas flow rate may vary manually or automatically, so that a constant residual chlorine concentration remains in the water flow to create concentrated chlorine solution. This mixture is left to the chlorinator as chlorine solution (HOCl) ready for implementation [8]. Typical feed rates of the smallest vacuum chlorinators range from approximately 10 to 100 g /h. The most commonly used vacuum chlorinators are the ones having the maximum operating capacities of 2 kg/h, 5 kg/h and 10 kg/h. Therefore, this makes it possible to use them in the medium cities as well as the metropolitan cities [3].

The main advantage of vacuum gas chlorinators is their safety. If a malfunction or breakage occurs in the vacuum system, the chlorinators stop the chlorine flow in the equipment or allow air to enter into the vacuum system instead of allowing the escape of chlorine into air [5]. Figure 2 shows gas chlorination plant.

Figure 2. Drinking water gas chlorination plant (Chlorine room, Chlorination Equipment, Chlorine tank)

Sodium Hypochlorite (Liquid Chlorination)

Sodium hypochlorite (NaOCl) is generally expressed as liquid bleach, and it is available as a solution containing chlorine between 5 and 20 percent. The color of this solution is light yellow, it has an alkali corrosion effect and a strong smell of chlorine. The typical concentration percentage used in sodium hypochlorite solution is based on commercial percentage and contains 12% chlorine [4,6].

Reaction of sodium hypochlorite with water is as follows.

$$NaOCl + H_2O \rightarrow HOCl + NaOH \quad (3)$$

Since they are safer, their use is easier and they pose fewer problems when they are poured, the use of sodium hypochlorite instead of chlorine gas in the water systems is usually preferred. But, the most important issue for sodium hypochlorite solution is the significant loss of available chlorine in time (usually maximum 90 days). Degradation rate increases with high solution strength and higher temperature [4]. The balance of the solution is greatly affected by light, pH, and heavy metal cations such as iron, copper and nickel. Dosing in the small drinking water plants where hypochlorite is used is carried out by the feed pump that is connected to the chlorine tank in a reliable manner. In order to avoid having trouble with feeding of water with daily chlorine, a spare pump must be available in order to be able to use another pump in an emergency when the pump breaks [4]. This disinfection is the most popular method used in rural areas. It is simple, easy and inexpensive and there are many devices that can use this technology. Diaphragm pump and venture type suction feeders are widely used to feed the solution [3]. Sodium hypochlorite storage room and feeding equipment are shown in Figure 3.

a) Diaphragm pump feeding system; The pumps in this system are equipped with one chamber, two one-way valves including one at the inlet and the other at the outlet point. The solution is added to the room through the suction valve, then the solution is discarded outside the room by the outlet valve as the diaphragm contraction, and this occurs through stimulation of the diaphragm by enlargement of electric motor. The flexible diaphragm is made of a material resistant to corrosive effects of hypochlorite solutions. The task of the pump is to increase the level of the solution through the stroke levels. The point of application may be a channel or a reservoir (atmospheric pressure), or a water pipe under positive pressure. This type of hypochlorinator has a large capacity. A small device feeds about 1 liter hypochlorite per hour and the biggest one feeds about 200 liters hypochlorite per hour. Depending on the concentration of the solution and the desired dose of chloride, a very variable water flow can be disinfected [3].

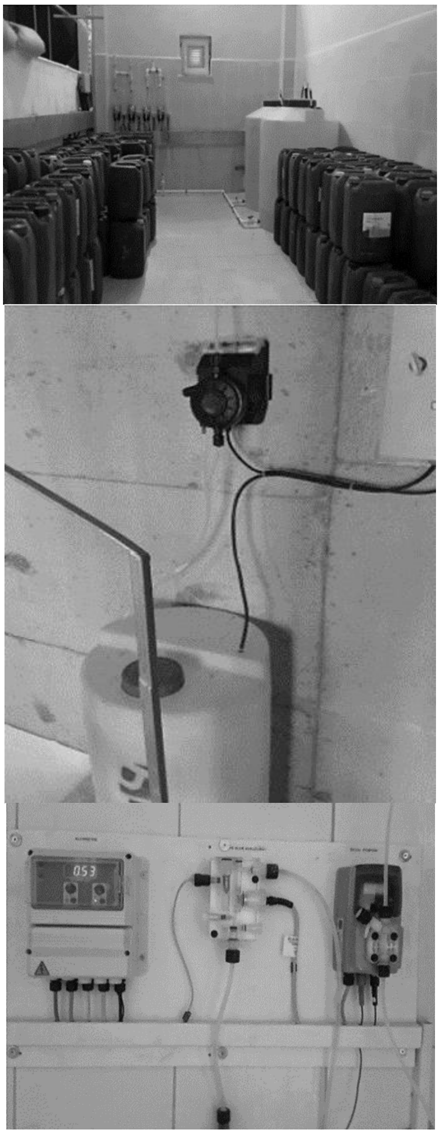

Figure 3. Drinking water sodium hypochlorite system

b) Suction feeders (venturi type); in common use, suction feeders use a venturi device in feeding chlorine solution along pressure pipe. Vacuum formed by the water flow from the venturi pipe absorbs hypochlorite solution and it is discharged directly to the main water supply. Feeding is controlled by a needle valve mounted between the venturi device and the rotameter. The installation, operation and maintenance of this device are easy and cheap. Feeding capacity varies between 1 to 25 L/h. An important advantage of this type of feeder is that the chlorine solution will not be released is water does not flow into the device, thus the possibility of overdose would be prevented. Venturi devices, depending on their design, can be mounted on the wall or directly to the pipes [3].

On-Site Sodium Hypochlorite Generation System (Salt Chlorination)

$$NaCl + H_2O + 2e^- \rightarrow NaOCl + H_2 \quad (4)$$

Salt Water Electron Sodium Hypochlorite Hydrogen

The generated sodium hypochlorite solution has a concentration of 0.8% by weight, about 0.8 grams available chlorine per liter, and a density of about 1010 g per liter [9]. The product is stable at low concentrations and is typically stored up to 24-36 hours. Hydrogen gas is a byproduct and the air in the tank is not explosive, but the storage tanks must be emptied in case of an explosion danger. The system is based on the dilute brine electrolysis which consists of on-site generation from high purity salt. The salt consumption to be spent to obtain the equivalent amount of chlorine in the registered systems is about 3 kg [5].

A fixed electric power source is needed to operate the on-site hypochlorite generators. In the absence of a fixed power, the generator can be used with the alternative solar panels and batteries. Until a few years before, these devices are not an alternative for the developing countries because of their complex technologies and high costs. Hypochlorite generators have become more popular devices as a result of use of new materials such as titanium in production of dimensionally stable anodes and improvements made in the power sources [3]. Since the storage conditions of the hypochlorite product have effect on the rate of deterioration of the product, they may also be effective on the overall efficiency of chlorine generation [5]. In this system, unlike the strong sodium hypochlorite solutions with concentrations between 12% and 15%, as a result of obtaining the final product that is the solution with a concentration of 0.8%, less crystallization occurs and it has less effect on pH of water. In addition to these advantages, 0.8% solution is typically classified as irritant health hazard. Thus, it can be exempted from the regulations specified in fire and building codes. In order to make comparison with other disinfection methods, local conditions, life cycle and cost analysis is performed and the feasibility of on-site sodium hypochlorite generation system is determined. Life cycle analysis, equipment and buildings, operation and maintenance, raw material and electrical energy costs should be included in the feasibility study [9].

The components of on-site sodium hypochlorite generation system

The components of on-site sodium hypochlorite generation system consist of water softener, salt saturation tank, soft water heater and chiller, brine measurement, electrolytic cell, brine diluter, rectifier, hydrogen dilution blowers, sodium hypochlorite storage tank, sodium hypochlorite feeding equipment. There are many different types of on-site sodium hypochlorite generation systems available and Figure 4 shows generation equipment.

The important variables that determine the overall effectiveness of this system are brine and dilution water feed rates; the temperature of dilute salt water entering the cell and electrode (in particular anode) status. Water is used both to prepare saturated brine and also in the electrolysis process to dilute brine came to the electrical cell. During electrolysis, calcium and magnesium salts that naturally exist in alkali waters with high pH in the cell will precipitate and dissolved quickly and reduce the electrolysis efficiency by accumulating on electrode surfaces. To prevent this, an ion exchange (cationic) softener is used to improve the water source to reduce the total hardness of feed water typically having less than 15 mg $CaCO_3$ per liter. Even though the natural hardness of the feed water is low, softening must be performed to enable removal of the precipitated iron and magnesium in the electrolytic cells and the electrodes [5].

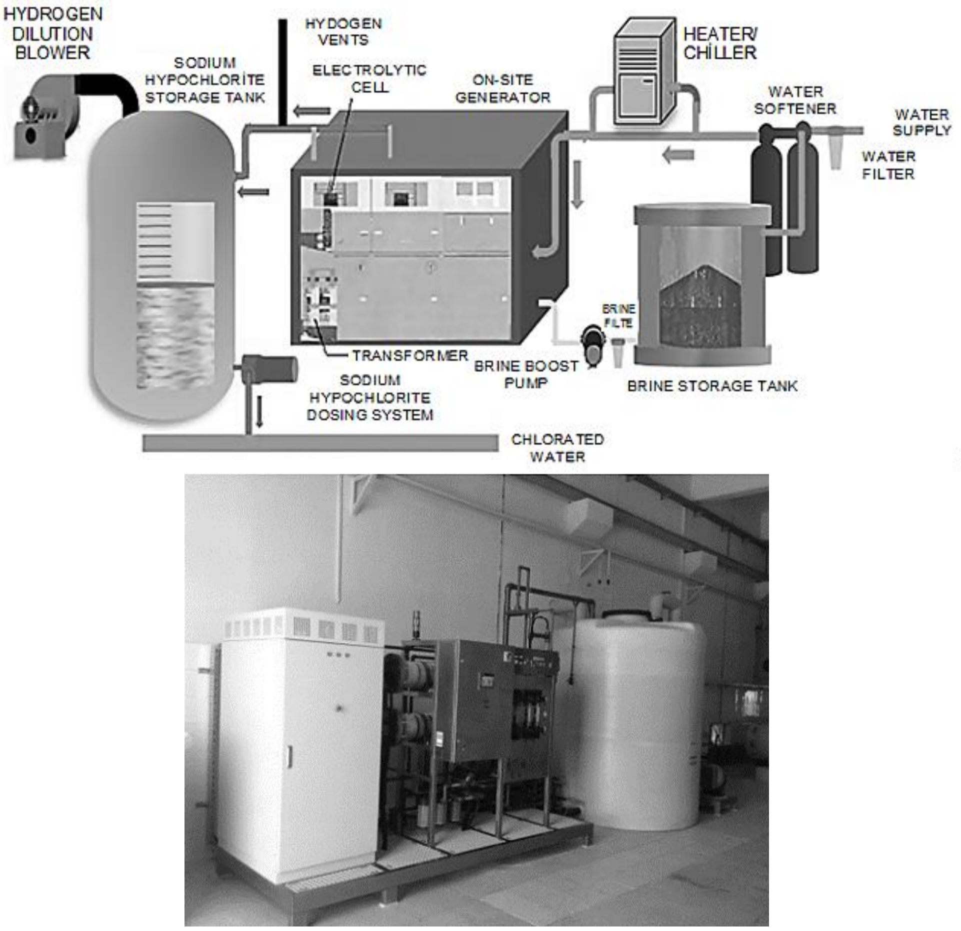

Figure 4. The equipment of on-site sodium hypochlorite generation system

Salt storage tank is composed of brine saturation mechanism, dust collection filter, salt level indicator and brine level indicator. The type made of glass fiber or fiber reinforced polymer and covered must be preferred for large systems and the type which can be opened from top and made of high density polyethylene must be preferred for the smaller systems. Tank sizes vary from manufacturer to manufacturer and tanks have different capacities depending on delivery of salt. Soft water heating and cooling is necessary to prevent unwanted movement of the reactions in the electrolytic cell and to maintain the water temperature [9]. Electrolyte plates that are the main component of the on-site sodium hypochlorite generation system is made of titanium. Electrodes have a maximum alternating current (AC) of 2.0 kW for 0.45 kg chlorine product. Energy requirement varies from manufacturer to manufacturer. Metal current density in the electrodes will increase the use of electricity and the consumption of salt and electrolytic cell efficiency will reduce, therefore they must be cleaned regularly. Hydrogen gas is generated during the electrolysis of sodium chloride solution. A portion of this gas is vented and the other portion goes to the cell with sodium hypochlorite solution. Due to the risk of fire and explosion hydrogen gas is worrisome. In order to prevent accumulation of flammable hydrogen gas, a general method, the elements such as hydrogen dilution balancing pipe, dilution blowers, gas sensors and high rates emergency ventilation system are used. Hydrogen gas is approximately 14.5 times lighter than air, therefore rises up quickly. Sodium hypochlorite solution is stored in FRP tanks. The storage time of on-site generated diluted sodium hypochlorite varies optionally but storage time is 3 days in case of average dose and flow rate but it is usually 1 day in case of maximum dose and maximum flow rate.

2. EXPERIMENTAL SECTION

The drinking water projects of Atalan-Osmaniye and Askale-Erzurum with flow rates of 10 L/sec and 59 L/sec have been selected as examples in this study. According to the statement 'the use liquid chlorine for disinfection in the plants having a drinking water flow rate of approximately 20 L/sec is economical' included in the “Drinking Water Treatment Plant Project Process Specification” of the ILBANK [8]. Sodium hypochlorite system (liquid chlorination) has been selected for the flow rate of 10 L/sec and gas chlorination system has been selected for the flow rate of 59 L/sec in these projects by our Bank. The systems selected according to the capacities indicated in the final projects of the subject works given in Table 1 and the ones calculated in Table 2 and the initial investment and operating costs of on-site sodium hypochlorite generation system will be compared.

The situation of selection of sodium hypochlorite system and on-site sodium hypochlorite generation system and the situation of selection of gas chlorination and on-site sodium hypochlorite generation system have been compared in the study.

Table 1. System equipment selected for sodium hypochlorite and chlorine gas

Chlorine System	Sodium Hypochlorite	Gas Chlorination
Flow rate (L/sec)	10	59
Chlorinator Capacity Selection (kg/h)	Dosing pump with a capacity of 0.487 L/h (1 + 1 Spare)	2 pieces of automatic gas chlorinator with 500 g/h capacity (1 +1 Spare), 2 pieces of vacuum regulator (1 +1 Spare) in compliance with them.
Chlorine requirement to be stored (for 15 days) (kg)	1 piece of PE tank with a capacity of 60 l + 3 pieces of 60 L bins	Chlorine cylinders (3 + 2 Spare)
Injector Selection	-	Chlorinator capacity is 500 g/h, and 1 g/h capacity injector has been selected accordingly.
Booster Pump Selection	-	Q=2m3/h Hm=3 bar Energy=220V 1 main pump and 1 spare booster pump with a characteristic of Power=1.5 kW will be placed.
Explanations	The final chlorine content is taken as 2 mg/l according to the İlbank specification.	
	Concentration of sodium hypochlorite solution that is commercially available is 0.12. In case of use of 60 L bins Dosing tank and bins will be placed in warehouse.	In case of use of 50 L chlorine cylinder The other equipment that have to be available; - EXHAUST FAN - louvre - Electrical heater will be used for heating. - Chlorine leakage sensor – warning (alarm device) will be placed. - Gas mask will be available. Gas chlorination equipment and cylinders will be placed in the chlorine building to be built next to the warehouse.

3. RESULTS AND DISCUSSION

The prices received from the companies dealing with chlorination system in Turkey have been used for comparison of the costs of the chlorination system in these plants. Table 2 and Table 3 Comparison of initial investment and operation cost for sodium hypochlorite and on-site hypochlorite generation system is given in below. 2015 prices are used in cost calculations.

Table 2. Comparison of sodium hypochlorite system-on-site hypochlorite generation system initial investment cost for flow rate of 10 L/sec

System Name	Equipment Used	Initial Investment Cost
Sodium Hypochlorite	- Dosing pump, - Liquid chlorine tank, - Sodium hypochlorite bin full	800£-5.804£
On-site Sodium Hypochlorite Generation	Generator and system equipment	12,920 £-16,044£
Note: Transport and installation are included in the prices.		

Table 3. Comparison of sodium hypochlorite system-on-site hypochlorite generation system operation cost for flow rate of 10 L/sec

SODIUM HYPOCHLORITE OPERATION COSTS						
Item No	Expenses	Unit	Life cycle (month)	Annual Amount (A)	Unit Price (B)	Annual Total Operation Costs (C=AxB)
1	Sodium Hypochlorite Quantity	Kg	12	6,412	2.63 TL	16,864 TL
GENERAL TOTAL:						16,864 TL
DAILY COST OF SODIUM HYPOCHLORITE (INCLUDING EVERYTHING)						46.20 TL/day
ON-SITE SODIUM HYPOCHLORITE GENERATOR OPERATION COSTS						
Item No	Expenses	Unit	Life cycle (month)	Annual Amount (A)	Unit Price (B)	Annual Total Operation Costs (C=AxB)
1	Salt Expense	Kg	12	1,893	0.3 TL	568 TL
2	Electrolysis Process Electricity Expense	kW	12	3818 (*)	0.25 TL	954.5
GENERAL TOTAL:						1,522.5 TL
ON-SITE SODIUM HYPOCHLORITE GENERATION DAILY COST (INCLUDING EVERTHING)						4.17 TL/day
(*) = Generators capacity varies depending on the device model of the manufacturer, the salt and electricity consumptions for unit chlorine requirement according to the HypoX VX 100 model of Kemisan company are 3kg and 4.5 kW respectively, the salt and electricity consumptions according to the AE 4 model of Hidrodos company are 3 kg and 7.7 kW respectively. Since electricity consumptions are different, the average value is taken.						

Comparison of initial investment and operation cost for chlorine gas and on-site hypochlorite generation system is given in Table 4 and Table 5 below.

Table 4. Comparison of gas system-on-site hypochlorite generation system initial investment cost for flow rate of 59 L/sec

System Name	Equipment Used	Initial Investment Cost
Gas	- Vacuum regulator, Chlorinator, Injector, Chlorine leak system, Collector, Booster pump, Chlorine gas leak detector, Safety kit, Ventilation fan and louvres, Electric heater, Indoor piping, fitting materials and PVC, etc. to be used during installation. Materials, 50 kg chlorine cylinder	6.115£-20.248£
On-site Sodium Hypochlorite Generation	Generator and system equipment	24.375 £ - 48.302 £
Note: Installation, workmanship and transportation are included in the prices.		

Table 5. Comparison of gas chlorine system-on-site hypochlorite generation system operation cost for flow rate of 59 L/sec

GAS CHLORINE OPERATION COSTS						
Item No	Expenses	Unit	Life cycle (month)	Annual Amount (A)	Unit Price (B)	Annual Total Operation Costs (C=AxB)
1	Gas Chlorine Quantity	kg	12	3,681	1.6 TL	5,889 TL
2	Booster Pump Electricity Expense	kW	12	43,200	0.25 TL	10,800 TL
3	Chlorine gas room Heating Expense	kW	6	15,120	0.25 TL	3,780 TL
4	Maintenance and Repair Expense	Set	12	1	1,500 TL	1,500 TL
GENERAL TOTAL:						20,471 TL
DAILY COST OF SODIUM HYPOCHLORITE (INCLUDING EVERYTHING):						56.08 TL/day
ON-SITE SODIUM HYPOCHLORITE GENERATOR OPERATION COSTS						
Item No	Expenses	Unit	Life cycle (month)	Annual Amount (A)	Unit Price (B)	Annual Total Operation Costs (C=AxB)
1	Salt Expense	kg	12	11,610 (*)	0.3 TL	3,483 TL
2	Electrolysis Process Electricity Expense	kW	12	17,211.5 (**)	0.25 TL	4,302 TL
3	Maintenance and Repair Expense	Set	12	1	between 1,200 - 500 TL	850 TL (average)
GENERAL TOTAL:						8,635 TL
ON-SITE SODIUM HYPOCHLORITE GENERATION DAILY COST (INCLUDING EVERTHING):						23.66 TL/day
(*) and (**) = Generators capacity varies depending on the device model of the manufacturer, the salt and electricity consumptions according to the HypoX VX 500 model of Kemisan company are 3 kg and 4.5 kW respectively, the generator capacity is 11.30 kg and the salt and electricity consumptions according to the VAULT 25 model of Hidrodos company are 3kg and 4.4 kW respectively.						

4. CONCLUSIONS

Today, the most widely used one among the materials commonly used for disinfection of drinking water is chlorine. The equipment of chlorine disinfection systems is simple and cheap and their use is simple, therefore the operators can be trained in a short time, and also the chlorine amount in the water main can be easily measured since it creates effective and lasting effect, if it is applied at a sufficient dose with low concentration. Chlorine is a disinfectant that can be found easily even in the developing countries.

In this study, the chlorine systems (gas and sodium hypochlorite) selected according to the flow rates in the ILBANK projects were examined by comparing them with sodium hypochlorite generation system in terms of initial investment and operating costs. It is seen in the comparison that the initial investment cost of the sodium hypochlorite generation system is expensive as compared to the other two systems, but its operating cost is more appropriate.

Before deciding the use of the systems to be used, it is required to perform a feasibility study to determine the ease of transport of municipalities to supply the raw materials for disinfection, their technical capacity and knowledge about use, operation and maintenance of equipment; their economic and financial capacity to meet the cost of investment, operation and maintenance as well as their economic and social situation. Life cycle analysis, equipment and buildings, operation and maintenance, raw material and electrical energy costs must be included in the feasibility study.

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