Novel Design of Vertical Undivided Electrochemical Cell with Concentric Electrodes for Continuous Production of Sodium Hypochlorite

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Abstract. The production of sodium hypochlorite (bleaching liquid) using an innovative electrode design in an undivided continuous electrochemical cell is the main goal of this work. The apparatus consists of two cylindrical concentric electrodes: the cathode is a stainless steel electrode with a diameter of 46 mm and a length of 400 mm, and the anode is a graphite rod with a diameter of 30 mm and lengths of 400 mm and 200 mm. This setup yields an annular column cell. This work investigates the effects of four key process factors on the concentration of sodium hypochlorite (NaOCl) in grammes per litre (g/l) and production efficiency: anode length, flow rate, current, and sodium chloride (NaCl) concentration. In a typical experimental setup, the following electrochemical cell characteristics are obtained with an anode length of 200 mm, a current of 8 A, a flow rate of 100 ml/min, and a NaCl concentration of 75 g/l: NaOCl concentration of 3.5 g/l, energy consumption of 2.2 kWh/kg, efficiency of 95.5%, capacity of 15.1 mol/m2.h, and space-time yield (STY) of 746 mol/m3.h.

1. Introduction

A hypochloric anion (OCl-) paired with a sodium cation (Na+) is the characteristic of the chemical compound sodium hypochlorite, denoted by the formula NaOCl. This material is hypochlorous acid (HOCl) in aqueous form; it is referred to as bleach or bleaching liquid when it dissolves in water [1]. The disinfection of water, bleaching of fabrics, cleaning of surfaces, and elimination of odours are only a few of its numerous applications [2]. In addition to chlorinating swimming pools and drinking water, sodium hypochlorite is commonly employed in bleaching processes in the paper pulp and textile industries [3]. The production of sodium hypochlorite involves two main procedures. In the first method, chlorine gas is directly reacted with a sodium hydroxide (NaOH) solution inside of an absorption tower to create a high concentration (up to 15%) of hypochlorite solution [4]. This process is shown in Figure (1). The chemical equation for this reaction is as follows:

$$2NaOH + Cl_2 \rightarrow NaOCl + NaCl + H_2O \quad \text{(Absorption tower)} \quad (1)$$
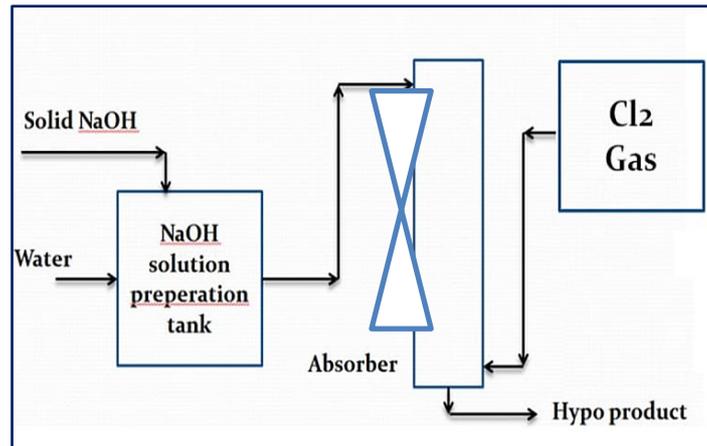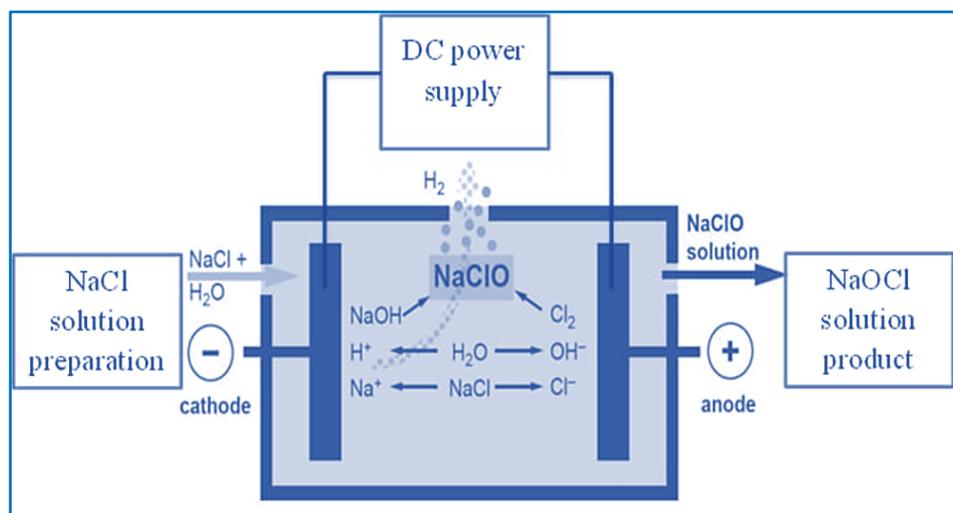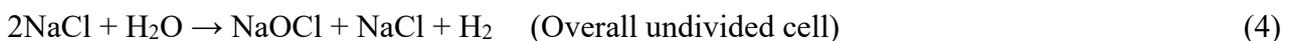
Fig. 1. The sodium hypochlorite production chemical process.

Another process for producing sodium hypochlorite is the direct electrochemical method, which involves electrolysis in a single cell. In this process, hydrogen and caustic soda are produced at the cathode while chlorine is produced at the anode. Sodium hypochlorite (NaOCl) is produced when the chlorine reacts with NaOH, as shown in Figure (2) [5]. The relevant reactions are shown in the following equations [6, 1, 7].

$$2NaCl + 2H_2O \rightarrow 2NaOH + Cl_2 + H_2 \qquad \text{(Undivided cell)} \qquad (2)$$

$$2NaOH + Cl_2 \rightarrow NaOCl + NaCl + H_2O \qquad \text{(Undivided cell)} \qquad (3)$$

The following is a representation of the overall chemical reaction:

$$2NaCl + H_2O \rightarrow NaOCl + NaCl + H_2 \quad \text{(Overall undivided cell)} \qquad (4)$$

Fig. 2. Shows an undivided cell that produces sodium hypochlorite.

In an efficient manner, a solution of sodium hypochlorite, which is a strong disinfectant, is produced using a salt and water solution that is electrolyzed in a process known as on-site electro-chlorination (OSEC)[8]. OSEC would have low operating costs overall and a less complex production that requires a power supply, salt, and water[9], as compared to the traditional chlorination processes. This design utilizes concentric vertical electrodes, unlike the conventional undivided cells, it enhances the distribution of the electrolyte, reduces the internal resistance, and allows compact, continuous operation. Recent studies reinforce the importance of operating conditions and cell configuration for efficient on-site electrochlorination (OSEC) and hypochlorite generation. Foundational electrochemical analyses describe how chloride oxidation pathways and mass-transfer/ohmic effects govern NaOCl selectivity and yield in undivided cells [10]. Practical

OSEC implementations and small-scale systems further document safe operation with brine electrolysis and highlight design considerations for continuous production [11]. More recently, bench-scale continuous-flow reactors using porous/flow-through electrodes have demonstrated improved hypochlorite productivity under controlled salinity, current, and spacing [12]. Other investigations have examined parameter effects (NaCl concentration, current/potential, hydrodynamics) and product speciation/efficiency in brine electrolysis for active chlorine generation [13]. In addition, emerging membrane-assisted concepts illustrate how reactor geometry and ion-transport management can enhance NaOCl formation while informing future cell designs [14]. These studies collectively motivate our concentric, vertical undivided cell as a compact configuration aimed at robust, continuous NaOCl production.In this study, we assess the performance of a novel vertical column including two concentric electrodes inside a single electrochemical cell to manufacture sodium hypochlorite continuously. Four significant process factors were examined for their influence on the concentration of NaOCl produced and process efficiency: the anode area (Aa), the salt solution concentration (C_{NaCl}), the solution flow rate (Q), and the current (I).

2. Experimental Work

2.1. Materials

All materials used in the present study are illustrated in Table 1 below. Sodium chloride is used for preparing the salt solution. All other chemicals are used for analysis of samples.

Table 1. Materials used in the study.

Materials	Purity	Supplier
Sodium chloride, NaCl	96.31%	Tikrit university
Distilled water, H_2O	98%	Tikrit university
Deionized water, H_2O	100%	Merck Germany
Sodium thiosulfate, $Na_2S_2O_3$	99%	Merck Germany
Potassium iodide, KI	99%	Merck Germany
Acetic acid, CH_3COOH	99.7%	Merck Germany
Starch Soluble, $(C_6H_{10}O_5)n$	99%	Merck Germany

2.2. Experimental Procedure

Figure (3) shows the schematic diagram of the experimental setup of undivided continuous electrochemical cells used. All experiments in this work were conducted using undivided electrochemical cells of electrolysis process of NaCl solution to produce sodium hypochlorite. Two concentric electrodes (like double pipe heat exchanger) are used, graphite (d = 30mm, L= 400mm) as anode and stainless steel (d = 46mm, L= 400mm) as cathode. The electrolyte was continuously pumped through a vertical cell with volume (0.382 L) from the bottom of the flow rate. To obtain large quantity of sodium hypochlorite various variables have been studied for this objective. The various variables studies were current, concentration of sodium chloride NaCl, length of anode and the flow rate, each experimental run consist of different concentrations of NaCl (25,50 and 75 g/L) and different applied current (6 and 8 A) and different lengths of anode (400 and 200mm). This study employed undivided continuous electrochemical cells, as seen in Figure 3. The electrolysis of NaCl solution yielded sodium hypochlorite, and this reaction was the main focus of all the studies conducted with these single electrochemical cells. The setup featured two concentric electrodes,

measuring d = 30 mm by L = 400 mm, that resembled a double-pipe heat exchanger: the anode was composed of graphite, while the cathode was constructed of stainless steel. Starting at the bottom, a vertical cell with a volume of 0.382 L was continually pushed through at a specified flow rate to ensure electrolyte circulation. Many factors were thoroughly investigated to generate significant volumes of sodium hypochlorite. These variables comprised the applied current, anode length, concentration of sodium chloride (NaCl), and flow rate. Each experimental session employed a different combination of applied currents (6 and 8 A), anode lengths (400 and 200 mm), and NaCl concentrations (25, 50, and 75 g/L). The process efficiency was calculated as the ratio of the actual NaOCl produced to the theoretical yield based on the total charge passed through the cell.
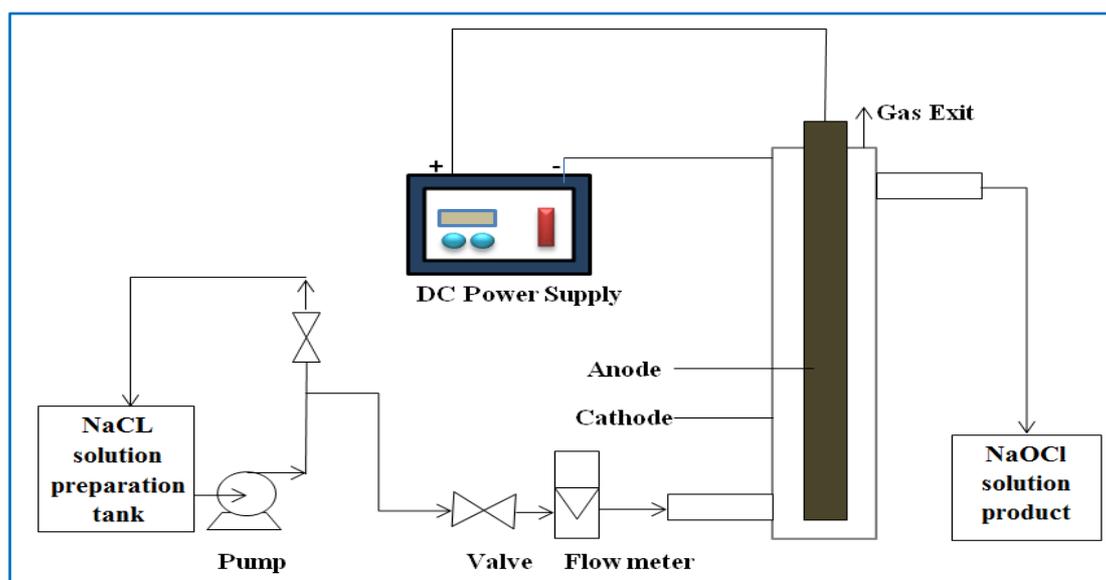

Fig. 3. Schematic diagram of the experimental setup.

2.3. Analytical Methods

Iodometric titration was used to measure the concentration of sodium hypochlorite. The levels of sodium hypochlorite (NaOCl) were measured in the laboratory using samples that were taken every thirty minutes [3].

3. Results and Discussions

The lack of direct comparison with previous studies is limited by the novelty of the current concentric electrode arrangement, which to the best of our knowledge has not been reported before.

3.1. Effect of Process Variables on the Concentration of Hypochlorite

3.1.1. Effect of NaCl Concentration

The relationship between the production of sodium hypochlorite (NaOCl) and the concentration of NaCl is seen in Figures (4) and (5). When the concentration of NaCl grows within the investigated range, the produced hypochlorite concentration increases under all process conditions. The observed trend can be explained by the fact that O2 evolution side reactions decrease in frequency as salt concentration increases. Nevertheless, at very high NaCl concentrations, chlorate may be generated. Consequently, it is commonly known that for industrial-scale hypochlorite (NaOCl) synthesis, using a high concentration of aqueous NaCl solution is recommended.
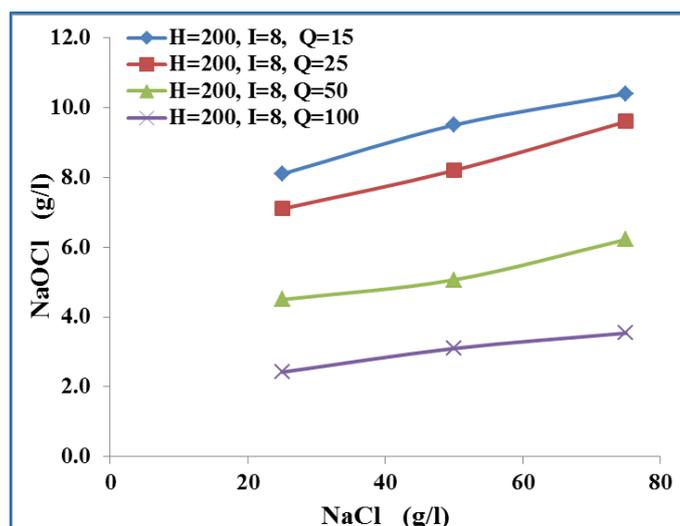
Fig. 4. Illustrates the relationship between hypochlorite concentrations at constant current intensities of 8 A and 200 mm of height (H) with varying flow rates and rising NaCl contents.
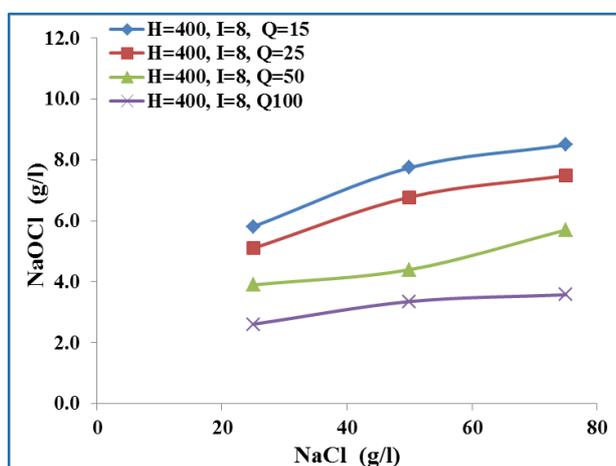

Fig. 5. depicts how different NaCl concentrations impact hypochlorite concentration at different flow rates while keeping electrode spacing (H = 400 mm) and current intensity constant (I = 8A).

3.1.2. Effect of Applied Current

Figures (6) and (7) demonstrate how current affects the generation of sodium hypochlorite (NaOCl). A current density is defined as the current flowing through the anode per unit area. It was found that independent of the process parameters, the concentration of hypochlorite rose when the current was raised within the examined range. This finding is consistent with the Faraday law equation from electrochemical analysis, which asserts that increasing current flow promotes the evolution of oxygen (O_2) or the cell's creation of chlorate. The temperature of the cell was also shown to increase with increasing current, which caused sodium hypochlorite to chemically break down into sodium chlorate.

$$NaClO_3 + 2NaCl \longrightarrow 3NaOCl \tag{5}$$
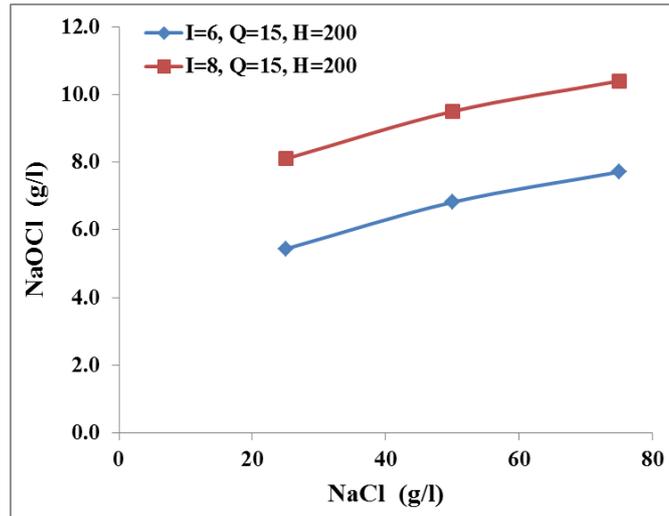
Fig. 6. Illustrates how increasing NaCl concentrations affect hypochlorite concentrations at different currents while keeping H at 200 mm and Q at 15 ml/min.
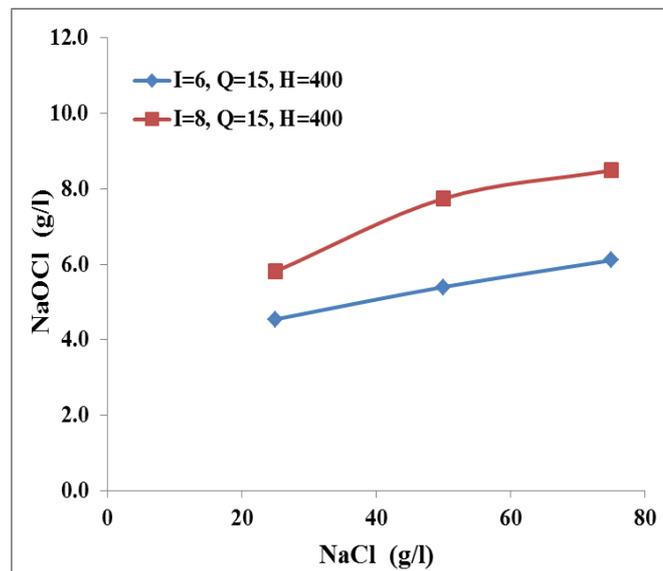

Fig. 7. shows the impact of increasing NaCl concentrations on hypochlorite concentrations at different current levels, with H fixed at 400 mm and a flow rate of Q=15 ml/min.

3.1.3. Effect of the Area Of Anode

Alterations in the anode's area, as determined by its height, impact the current density and the internal placement of the anode within the annular column electrochemical cell used in this work in two different ways. The effect of anode size on the yield of sodium hypochlorite (NaOCl) is seen in Figure 8. In most process circumstances that have been studied, a drop in current density often results in a decrease in the concentration of generated hypochlorite as the anode's area expands. In this work, the density range (159.2 to 424.4 A/m^2) is examined, however it is still too little to have a negative impact on the concentration of hypochlorite. This finding can be explained by the effect of the anode's location within the cell. At low solution flow rates, the breakdown of produced hypochlorite is facilitated by increasing the anode's area to the height of the cell column (H=400 mm). This effect is less apparent at higher flow rates (100 ml/min), though. Figure 9 shows that the positioning of the anode has less of an influence at flow rates greater than 50 ml/min.
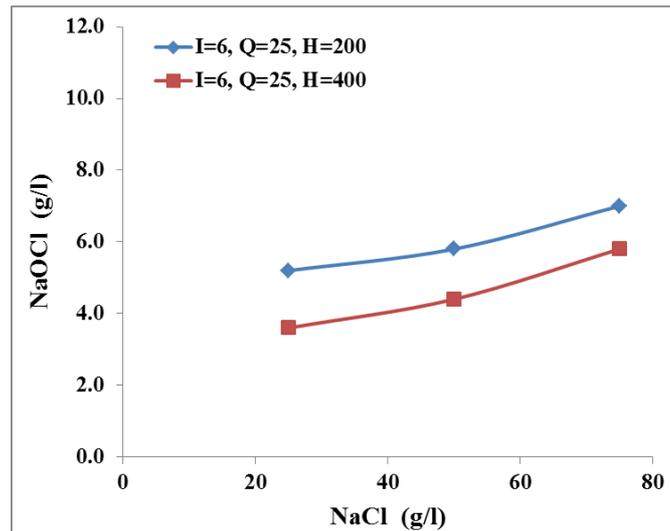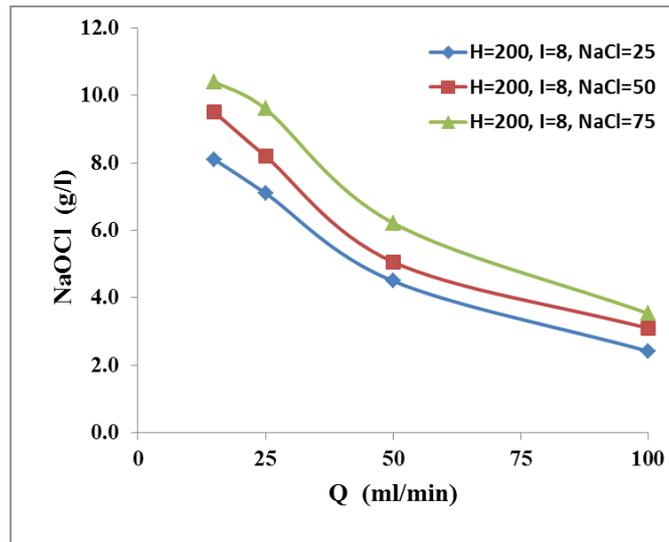
Fig. 8. Effect of NaCl concentration on hypochlorite concentration at different H and constant I=6 A, Q=25 ml/min.
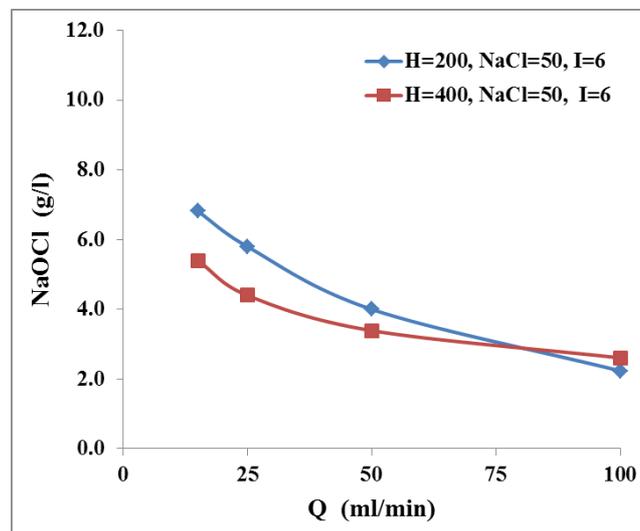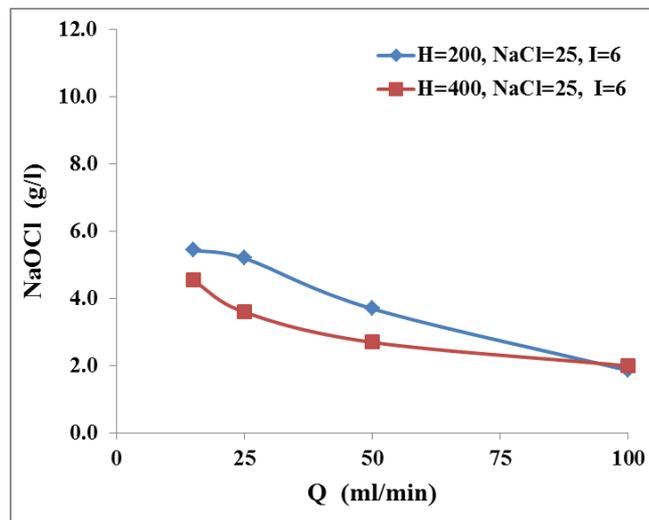

Fig. 9. Effect of flow rate on hypochlorite concentration at different H and constant C_{NaCl}=50 g/l, I=6 A.

3.1.4. Effect of Flow Rate

The variation in sodium hypochlorite (NaOCl) concentration with flow rate is seen in Figure 10. During the experimental tests, the flow rate ranged from 15 to 100 ml/min. It was demonstrated that when the flow rate increased, the concentration of hypochlorite decreased for all process parameters examined within the range. The phenomenon is caused by the decrease in electrolysis time with increasing flow rate (t=Vc/Q). Furthermore, the flow rate and other process parameters, such as the location of the anode electrode, interact to affect the concentration of produced sodium hypochlorite (NaOCl). As Figure 11 shows, electrode location becomes less significant when flow rates go over 50 ml/min.

Fig. 10. Effect of flow rate on hypochlorite concentration at different NaCl concentration and constant H=200 mm, I=8 A.


Fig. 11. Effect of flow rate on hypochlorite concentration at different H and constant C_{NaCl}=25 g/l, I=6 A.

3.2. The Effect of Process Variables on the Process Efficiency

### 3.2.1. Effect of Sodium Chloride Concentration

Figure 12 illustrates how the concentration of sodium chloride affects process efficiency. In every experiment, a concentration of NaCl ranging from 25 to 75 g/l was used. Efficiency steadily rose as NaCl concentrations were raised within the examined range of process conditions. The improved performance is attributed to the reduced side reaction involving O_2 evolution, which is enabled by a greater salt concentration. Interestingly, the NaOCl concentration peaked at 10.4 g/l at 8 A and 15 ml/min flow rate, with an anode height of 200 mm and a NaCl concentration of 75 g/l.
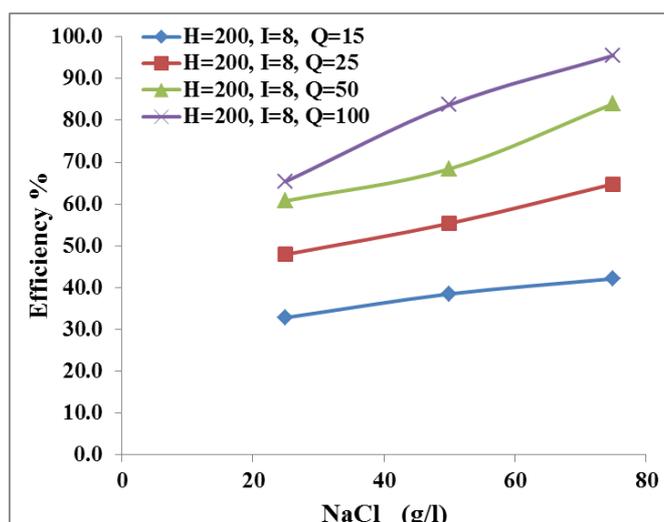
Fig. 12. Effect of NaCl concentration on process efficiency at different flow rates and constant I=8 A, H=200 mm.

3.2.2. Effect of Applied Current

Figure 13 displays the effect of current on process efficiency. It is apparent that efficiency varies not substantially with the increase of the current across all conditions of the processes studied. The scale of the currents in this experiment 6 to 8 A is sufficiently low that it will not have any adverse effects on the concentration of the hypochlorites in solution and the overall efficiency of the process. The consistency in the concentration of NaOCl that was observed under these experimental conditions indicates that there were no significant side reactions, including the formation of chlorates and decomposition of hypochlorites. While a full benchmarking with commercial OSEC systems was beyond the scope of this proof-of-concept study, the NaOCl concentrations and efficiencies obtained fall within the ranges reported in previous literature.
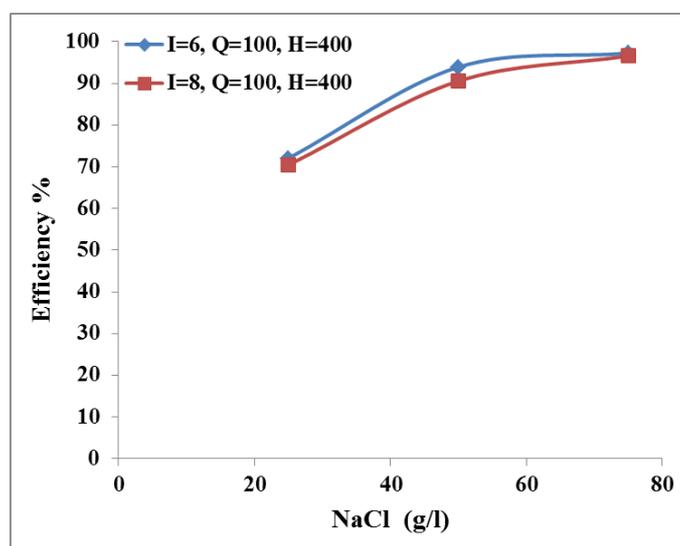

Fig. 13. Effect of NaCl concentration on process efficiency at different currents and constant H=400 mm, Q=100 ml/min.

3.2.3. Effect of the Area of Anode

This work investigates two important impacts of the anode area in the annular column electrochemical cell: the displacement of the anode inside the cell and the changes in the current density. The study aims to optimise hypochlorite concentration and process efficiency by focusing on current densities ranging from 159.2 to 424.4 A/m² and current ranges of 6 to 8 A. Figure 14 shows how changing the anode area affects process efficiency. Increasing anode area typically

resulted in decreased efficiency in the majority of the scenarios studied, with the exception of high flow rate circumstances (100 ml/min), when efficiency increased with anode area. This outcome is most likely connected to where the anode is located within the cell. Anode expansion to the full column height (H=400 mm) promotes hypochlorite breakdown, particularly at lower solution flow rates. However, at high flow rates (100 ml/min), hypochlorite decomposition loses efficacy.
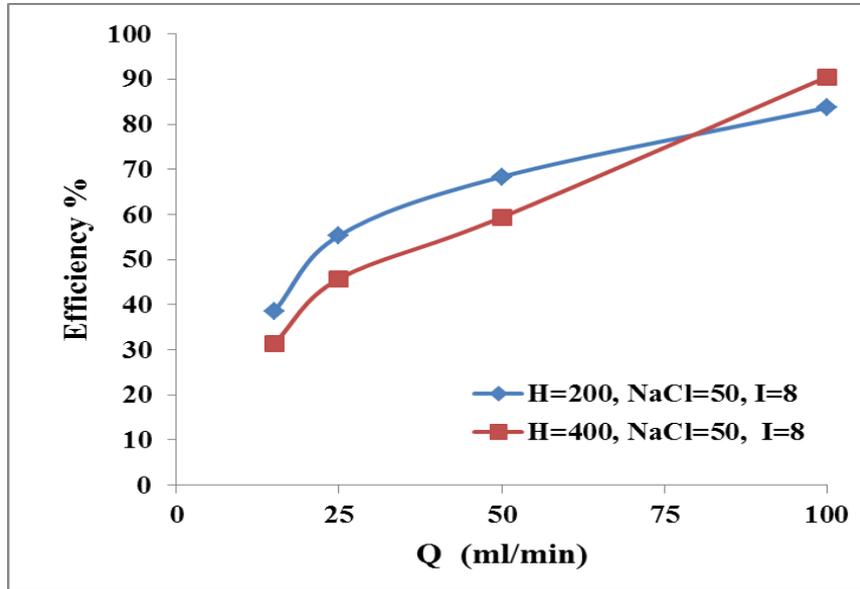
Fig. 14. Effect of flow rate on process efficiency at different H and constant C_{NaCl}=50 g/l, I=8 A.

3.2.4. Effect of Flow Rate

The relationship between process efficiency and flow rate is seen in Figure 15. The relationship between flow rate and efficiency is direct, while the relationship between flow rate and NaOCl concentration is inverse. Higher flow rates were linked to increased efficiency across the board for the process parameters that were examined. The improvement in efficiency is caused by the fact that as the flow rate rises, the rate of hypochlorite breakdown decreases, shortening the residence time (t=Vc/Q) of the process.
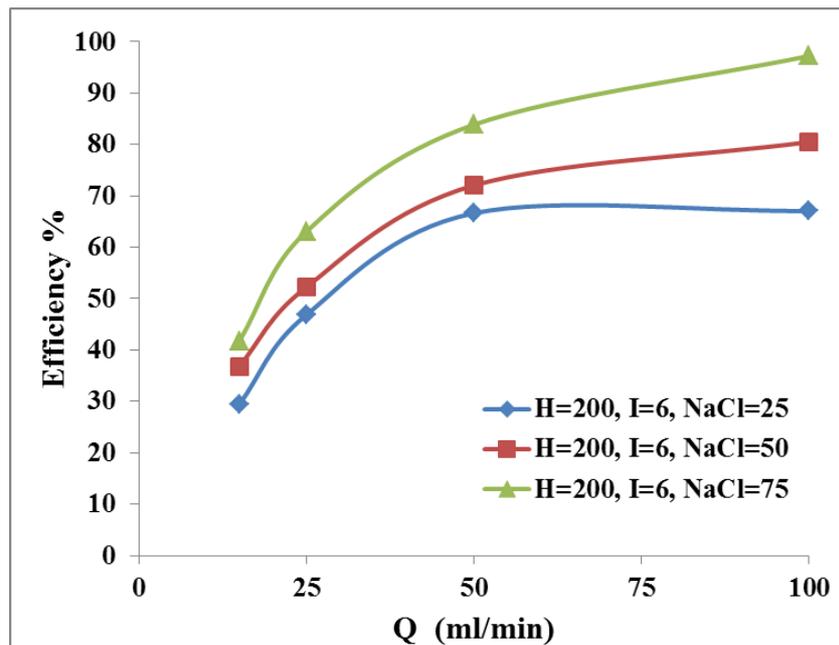
Fig. 15. Effect of flow rate on process efficiency at different NaCl concentration and constant H=200 mm, I=6 A.

4. Conclusion

This work investigated a new design for a vertical undivided electrochemical cell that uses concentric electrodes to continually manufacture sodium hypochlorite. Sodium hypochlorite was efficiently produced in a continuous electrochemical cell arrangement by use of a unique electrode design, which consisted of two cylindrical concentric electrodes creating an annular column cell. The concentration of generated hypochlorite and process efficiency increased as the NaCl content increased within the evaluated range of process parameters. In all the process settings that were studied, higher hypochlorite concentrations were linked to higher current levels; however, there was no discernible effect of increased current on efficiency. On the other hand, when the hypochlorite content decreased, higher flow rates were linked to an increase in process efficiency. The concentration of hypochlorite dropped when the anode area was increased from 200 to 400 mm, despite a decrease in the current density. Regretfully, the hypochlorite content did not drop within the employed current density range of 159.2 to 424.4 A/m2. Anode area increased with efficiency at low flow rates (between 15 and 50 ml/min) but increased with efficiency at high flow rates (between 100 and 200 ml/min). In a typical experiment with the provided conditions, the electrochemical cell yielded the following results (H=200 mm, I=8 A, Q=100 ml/min, NaCl concentration=75 g/l): The NaOCl concentration is 3.5 (g/l), the capacity is 15.1 mol/m2/h, the STY is 746 mol/m3/h, the electric power is 2.2 kW h/kg, and the efficiency is 95.5%.

Acknowledgement

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