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# The hydrodynamic behavior of a parallel-plate electrochemical reactor

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## HIGHLIGHTS

- ▶ The hydrodynamic behavior of parallel-plate electrochemical reactor was study.
- ▶ The experiments provide evidence of the plug-flow character of the reactor.
- ▶ The Brinkman equation was applied to describe the behavior of flow.

## ARTICLE INFO

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## ABSTRACT

The aim of this study was to characterize the hydrodynamic behavior of a parallel-plate electrochemical reactor (PPER) and its net-type spacer. Consequently, the residence time distributions (RTDs) and flow visualization (FV) of the PPER were measured. In addition, platinum was electrodeposited onto the surface of the titanium electrode (cathode) of the PPER. Subsequently, a complementary computational fluid dynamics (CFD) study was performed to aid in data analysis. The axial dispersion coefficient was found to increase linearly with the flow rate, and all data corresponded to a signal in the form of an instantaneous impulse at the reactor inlet that could be detected immediately at the reactor outlet. These experiments provided evidence that the plug flow predominated for all gaps that were tested, and the platinum coating showed a thickness distribution that corresponded to the concentration profile that was predicted by the CFD study. Thus, the experimental thickness distributions verified the results of the CFD study. The Brinkman equation for porous media flow was proposed to describe the behavior of the flow that was observed in the FV experiment, and we found that the PPER could be used in further research for hydrogen production.

## 1. Introduction

Hydrogen is an excellent candidate for a future ideal, clean fuel. Hydrogen can be produced in an electrolyzer (i.e., an electrochemical cell used for electrolytic processes), which is frequently arranged by stacking cells that are made up of planar plates of electrodes and membranes covered with several "inner" frames that consist of plastic nets, which are commonly termed "turbulence promoters". Houghton et al. [1] reviewed parallel-plate cells and commented that a common practice was to place hydrodynamic obstructions in the flowing stream to break up the mass transfer boundary layer, which consequently increased the rates of mass transfer. Specifically, net-type spacers have two essential functions. First, they keep adjacent electrode leaves apart so that a feed channel is formed. Second, they promote mixing between the bulk of the fluid and the fluid element that is adjacent to the electrode surface.

Residence time distribution (RTD) is an essential tool for analyzing electrochemical reactors to detect deviations from ideal plug flow, which can be caused by the presence of stagnant regions and the existence of regions with low resistance to flow (by-passing). The behaviors of residence times of parallel-plate electrochemical reactors (PPERs) have been studied extensively for more than 15 years [1–15], and the hydrodynamics of PPERs have been studied using computational fluid dynamics (CFD) [9,10,15,16]. In addition, studies of flow visualization (FV) for PPERs have been reported previously [4,5]. However, Fimbres-Weihs and Wiley [16] reviewed the studies for the 3D CFD modeling of flow in net-type spacers in laminar steady flow and turbulent flow regimes and concluded that vortices play a primary role in mass transfer enhancement. In particular, the most studied PPER is the FM01-LC, which is a laboratory-scale reactor based on a larger, industrial electrolyzer (INEOS Chlor-Chemicals). The RTD, FV and CFD techniques were usually employed to study the flow patterns of FM01-LC reactors and its net-type spacers in turbulence and laminar regimes [3,5,7,9–11,15]. However, these phenomena are still not fully understood. For example, the net-type spacer studied in this work has parameters that are

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**Nomenclature**

*Latin letters*

| | |
|---|---|
| $A$ | flow field area dimension (m) |
| $A_{cross\text{-}section}$ | cross-sectional area (m$^2$) |
| $A_g$ | geometric area of electrode (m) |
| $A_r$ | electrochemical surface area (m) |
| $C$ | concentration (mol/l) |
| $c_i$ | initial dye concentration (mol/l) |
| $d_c$ | inter-electrode gap (m) |
| $d_e$ | hydraulic diameter of the channel (m) |
| $D_0$ | axial dispersion coefficient |
| $D_i$ | diffusion coefficient (m$^2$/s) |
| $E(t)$ | the normalized experimental concentration (s$^{-1}$) |
| $E'(t)$ | normalized concentration in fitting equation (s$^{-1}$) |
| $F$ | Faraday's constant (C mol$^{-1}$) |
| $f_r$ | roughness factor |
| $i$ | density current (A/m$^2$) |
| $k$ | permeability of the porous media |
| $l$ | length of the cell (m) |
| $M$ | number of moles electrodeposited |
| $n$ | number of electrons |
| $p$ | pressure (Pa) |
| $Pe$ | Peclet number |
| $Q$ | charge of a full monolayer of adsorbed hydrogen (μC cm$^{-2}$) |
| $Q_e$ | experimental charge passed (μC cm$^{-2}$) |
| $Q_v$ | volumetric flow rate (m$^3$/h) |
| $Re$ | Reynolds number |
| $u$ | $u = Q_v/A_g t$ mean superficial fluid velocity (m s$^{-1}$) |
| $\mathbf{u}$ | velocity vector (m/s) |
| $u_0$ | inlet flow velocity (m/s) |
| $V$ | volume of the detector (m$^3$) |
| $w_c$ | width of the reactor (m) |

*Greek symbols*

| | |
|---|---|
| $\varepsilon$ | porosity of the spacer (void fraction of the cell) |
| $\eta$ | dynamic viscosity of the fluid (N s/m$^2$) |
| $\rho$ | density of the fluid (kg/m$^3$) |
| $\tau$ | main residence time (s) |
| $\theta$ | dimensionless time |
| $\nu$ | kinematic viscosity (m$^2$ s$^{-1}$) |
| $\kappa$ | permeability of the porous medium (m$^2$) |

commonly reported in the spacers of electrochemical reactors [7,8,13]; however, the plug flow character of the reactor cannot be asserted a priori without studies on the performance of this net-type spacer. Furthermore, predictions of the behavior produced for the manifolds of the spacer and the geometry of this particular PPER are difficult without FV measurements.

Studies of the PPER and net-type spacer used in this work have not been previously reported. Therefore, the purpose of this initial study was to improve the understanding of the hydrodynamics of this particular reactor and its net-type spacer.

This particular PPER will be used in further research for the production of hydrogen and sodium hypochlorite. Hydrogen can be used in a fuel cell to generate electricity, and sodium hypochlorite can be used to purify potable water [17].

## 2. Experimental

### 2.1. Materials and equipment

All reagents were analytical grade and were used upon arrival. All solutions were prepared with Milli-Q water, and the reactor was a press-filter-type reactor from Asahi Glass Co. (Japan) DS-0, which included batch recirculation in the operational mode. Table 1 shows the equipment specifications. The aqueous tracer solution flowed through a plastic schedule-40 polyvinyl chloride (PVC) pipe with a diameter of 2.54 cm. The hydraulic pump (Aromag 65/90 W AC) propelled the electrolyte solution from the storage tank to the PPER, through the pipe, and back to the storage tank. In addition, a bypass was introduced to obtain a suitable control of the flow rate at each inlet. The flow was measured using a flowmeter (Blue-White, F-460). For residence time distribution and flow visualization experiments, the PVC tube was connected to Masterflex® tubing, which was located in the inlet of the PPER.

The image in Fig. 1 shows the dimensions of the Asahi Glass high-density polypropylene net-type spacers. The plastic nets consist of a lattice of triangular threads that are similar to the Vexar-type interweaved net from DuPont or Expamet PV876 from Netlon Co. [18]. This net is marked as "L" in Fig. 1. The plastic net was characterized by different parameters, such as the distance between the spacer filaments and the diameter of the filaments. However, in this work,

**Table 1**
Equipment specification.

| | |
|---|---|
| Flow field area dimension | 0.16 m × 0.24 m |
| Inner cell frame dimension | 0.10 m × 0.18 m |
| Anode plate | Platinum-plated titanium |
| Cathode plate | Stainless steel 316L |
| Thickness of the polypropylene spacer | 0.75 mm (7.5 × 10$^{-4}$ m) |
| Porosity of the spacers with diamond shaped mesh | 0.8062 |

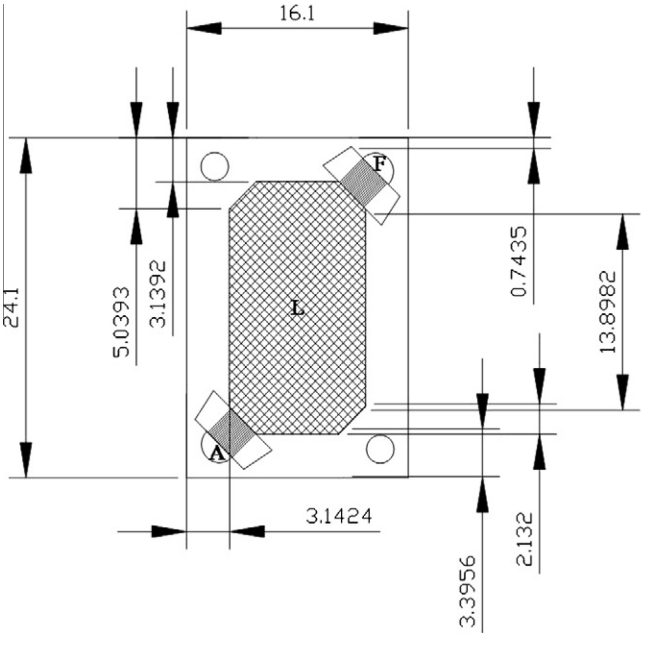

**Fig. 1.** The drawing and dimensions of the spacer in cm.

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