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# Uninterrupted swirling motion facilitating ion transport in electrodialysis

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## HIGHLIGHTS

- Mass transport enhancement with swirling motion introduced by twisted tapes
- 40% rise in mass transfer with twisted tapes compared to empty flow channel
- Axial alignment of twisted tapes to flow resulted in higher *Sh* per *Pn*.
- Interrupting swirling motion lowered *Sh* and increased *Pn*.

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## ABSTRACT

Performance analysis (ion transport per unit power consumption) of three different classes of flow promoters e.g. (i) twisted tape, (ii) twisted tape with cuts, and (iii) rod was tested in an electrodialysis setup with rectangular flow channel of fixed aspect ratio. Pressure drop inside flow channel with each flow promoter geometry was estimated at four different flow rates (5, 10, 15, 20 LPH). Comparison of Sherwood number, *Sh*, power number, *Pn*, Reynolds' number, *Re* and friction factor, *f*, indicated relative performance of any geometry with reference to the empty channel. 40% rise in *Sh* was recorded with monolayer layer twisted tape with spacing per unit membrane gap, $d/h = 5.3$ relative to empty channel. It is also reported that reduced spacing i.e. lower $d/h$ did not show consistent improvement in ion transport. Twisted tapes causing uninterrupted swirling motion showed 80% better performance compared to twisted tape with cuts which caused an interrupted swirling flow at $Re \sim 276$.

## 1. Introduction

Concentration polarization is a common phenomenon that limits the performance of electrodialysis (ED) process. The difference in the transport number of counter ions in solution compared to that in ion exchange membrane leads to development of concentration gradient at the membrane-solution interface. Depletion of salt concentration takes place in diluate (feed) compartment while concentration build up occurs in concentrate compartment. Once counter ion concentration near membrane surface on the diluate side approaches zero, limiting current density (LCD) appears, indicating the maximum rate of ion transport. This limiting current value can be further improved by reducing the concentration polarization near the membrane surface. This enhancement can be achieved by placing flow promoters called spacers inside flow channel, using corrugated membrane surfaces, air purging in the flow channel, membrane surface vibrators, ultrasonic field, flow vibration etc. [1,2].

Spacers of different geometries were reported earlier [2–6] to create mixing and impart mechanical stability to the channel geometry. Net spacers are most common flow promoters which break the concentration polarization by inducing a tortuous flow inside the channel core. Appropriate flow promoters capable of reducing concentration polarization by either minimizing the diffusion boundary layer thickness or almost disrupting it at low pumping cost will be of great importance.

Isaacson et al. [7] applied rod type promoters and reported four times improvement in mass transfer with proper geometrical arrangement. Tadimeti et al. [8] and Shaposhnik et al. [9] reported application of corrugated flow channels where the concentration polarization can be effectively minimized without causing any shadow effect. A multilayer sandwich spacer (twisted tape in between two non-woven net spacers) geometry developed by Li et al. [10] resulted 30% improvement in Sherwood number (i.e. measure of ion transport) compared to traditional nonwoven net spacers at the same power consumption. Balster et al. [11] extended the idea of multi-layer spacers of Li et al. [10] to develop systematic spacer geometries with minimum pressure drop and adequate mixing. Recently Fritzman et al. [12,13] reported closely spaced double stranded twisted filaments, which were systematically arranged parallel to the flow direction. They imparted swirling motion

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**Nomenclature**

List of symbols

| | |
|---|---|
| $C_b$ | concentration of ions in bulk, $\text{mol}\cdot\text{m}^{-3}$ |
| $C_m$ | concentration of ions at membrane surface, $\text{mol}\cdot\text{m}^{-3}$ |
| $D$ | diffusivity, $\text{m}^2\cdot\text{s}^{-1}$ |
| $D_h$ | hydraulic diameter, m |
| $F$ | Faradays constant, 96,500 $\text{C}\cdot\text{geq}^{-1}$ |
| $f$ | friction factor |
| $h$ | intermembrane distance, m, |
| $i$ | current density, $\text{A}\cdot\text{m}^{-2}$ |
| $i_{lim}$ | limiting current density, $\text{A}\cdot\text{m}^{-2}$ |
| $k$ | average local mass transfer coefficient, $\text{m}\cdot\text{s}^{-1}$ |
| $L$ | length of flow channel, m |
| $Pn$ | power number |
| $\Delta P$ | pressure drop, Pa |
| $Re$ | Reynolds number |
| $Sc$ | Schmidt number |
| $Sh$ | Sherwood number |
| $t_{bl}$ | transport number of ion in diffusion boundary layer |
| $t_m$ | transport number of ion in ion exchange membrane |
| $u$ | velocity, $\text{m}\cdot\text{s}^{-1}$ |
| $z$ | charge of ion |
| $\rho$ | solution density, $\text{kg}\cdot\text{m}^{-3}$ |
| $\mu$ | solution viscosity, $\text{N}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ |
| $\delta$ | diffusion boundary layer thickness, m |

to the entering stream and minimized concentration polarization in cross flow ultrafiltration.

Simulations of flow geometries reported by earlier researchers [10] revealed that even non parallel alignment (with reference to flow direction) of twisted tapes causes longitudinal vortices. These longitudinal vortices are very much similar to the swirling motion caused by the twisted tapes when aligned parallel to the flow. The parallel orientation of twisted tape requires their alignment to be in much closer proximity therefore, larger number of twisted tapes (in parallel direction) are required to cause similar mixing effect of a single twisted tape aligned non parallel to the flow [12].

Based on the discussion so far, it is understood that promoters create swirling motion near membranes and improves ion transport by minimizing concentration polarization. In case an interruption is introduced in the swirling flow profile by placing a cut on the tape, how will ion transport get affected was not explored earlier. Therefore, present report investigates the influences on ion transport caused by swirling motion causing twisted tapes (TT), interrupted swirling motion causing twisted tape with cuts and conventional rod type flow promoters.

## 2. Theory

It is assumed that the current density, $i$ inside an electrodialysis setup follows Faraday's law and is expressed as [14–16]

$$i = \frac{DzF(C_b - C_m)}{\delta(t_m - t_{bl})} \tag{1}$$

where, $t_m$ and $t_{bl}$ are the transport numbers of the ion inside membrane matrix and in diffusion boundary layer respectively, $D$ is the diffusivity of ions, $z$ is the charge of ion, $F$ is Faradays constant, $C_b$ and $C_m$ are the concentrations of ion in bulk and at the membrane surface respectively, while, $\delta$ is the diffusion boundary layer thickness and is commonly expressed (Eq. (2)) as a ratio of diffusivity $D$ and average local mass transfer coefficient, $k$ over the exposed membrane area [14–16].

$$\delta = \frac{D}{k} \tag{2}$$

Substituting Eq. (2) in Eq. (1) $k$ can be expressed as:

$$k = \frac{i(t_m - t_{bl})}{zF(C_b - C_m)} \tag{3}$$

For an applied potential once the concentration of ions over membrane surface approaches zero the current through the ED assembly becomes limiting, $i_{lim}$ and any further increase in potential doesn't show appreciable change in current density unless water splitting starts. Therefore, at limiting condition Eq. (3) reduces to the following expression:

$$k = \frac{i_{lim}(t_m - t_{bl})}{zFC_b} \tag{4}$$

Higher limiting current improves ion transport ($k$) and performance of any spacer was estimated from this parameter while keeping the input energy unchanged at a given flow rate i.e. Reynolds number ($Re$) should be estimated in the flow channel after appropriately correcting velocity due to volume occupancy of spacer. Sherwood number is a function of mass transfer coefficient, characteristic length and diffusivity. Geometry specific correlations which are applicable within a fixed velocity ($Re$) range (from literature) are commonly used to estimate local mass transfer coefficient. The expression for average Sherwood number, $Sh$ is expressed by [10]

$$Sh = \frac{kh}{D} \tag{5}$$

where, $h$ is the inter membrane distance and $D$ is the solute diffusivity.

The power consumed for pumping the fluid through each flow channel geometry may be expressed using Power number, $Pn$. This is based on pressure drop measurement over the length of the test section ($L$), characteristics length (inter membrane spacing) of fluid flow channel and physical properties of the electrolyte (density $\rho$, viscosity, $\mu$). The power number is defined as [10,11]:

$$Pn = \frac{\Delta P u \rho^2 h^4}{L\mu^3}. \tag{6}$$

Once the flow is fully developed the pressure drop is a function of $Re$ alone for an empty channel while in presence of flow promoters it becomes function of both $Re$ and $L/h$ inside flow channel. Sherwood number versus power number plots were used earlier to report the performance of spacers in literature [3,10,11]. Spacer geometries with higher $Sh$ per $Pn$ are considered to be more efficient.

## 3. Experimental

### 3.1. Flow promoter geometry and arrangement

Three different classes of flow promoters were chosen twisted tape (TT) (A–G), twisted tape with cuts at regular interval (H) and rod type promotes (I–K). Only G type spacer is of double layer (woven) category, while the rest are of monolayer type. Polypropylene sheet of 0.06 cm thick was cut into 0.4 cm wide tape which was twisted into shape of rope with a size of each turn Fig. 1 (a). The tapes were twisted to obtain a required number of twist per unit length (0.5/cm) and the number of twist per unit length was kept constant for all experiments involving twisted tape. The spacing between tapes ($d$), flow attack angles $\alpha$ (alpha) and $\beta$ (beta), lengths of the tape oriented in the flow channel