

Mass transfer in 3D printed electrolyzers: The importance of inlet effects

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Abstract

This paper investigates the effect of inlet shape, entrance length and turbulence promoters on mass transfer by using 3D printed electrolyzers. Our results show that the inlet design can promote turbulence and lead to an earlier transition to turbulent flow. The Reynolds number at which the transition occurs can be predicted by the ratio of the cross-sectional area of the inlet to the cross-sectional area of the electrolyzer channel. A longer entrance length results in more laminar behavior and a later transition to turbulent flow. With an entrance length of 550mm, the inlet design did no longer affect the mass transfer performance significantly. The addition of gyroid type turbulence promoters resulted in a factor 2 to 4 increase in mass transfer depending on inlet design, entrance length and the type of promoter. From one configuration to another, there was a minimal variation in pressure drop (<16 mbar).

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Abstract

This paper investigates the effect of inlet shape, entrance length and turbulence promoters on mass transfer by using 3D printed electrolyzers. Our results show that the inlet design can promote turbulence and lead to an earlier transition to turbulent flow. The Reynolds number at which the transition occurs can be predicted by the ratio of the cross-sectional area of the inlet to the cross-sectional area of the electrolyzer channel. A longer entrance length results in more laminar behavior and a later transition to turbulent flow. With an entrance length of 550mm, the inlet design did no longer affect the mass transfer performance significantly. The addition of gyroid type turbulence promoters resulted in a factor 2 to 4 increase in mass transfer depending on inlet design, entrance length and the type of promoter. From one configuration to another, there was a minimal variation in pressure drop (<16 mbar).

Topical Heading and Key Words

Transport Phenomena and Fluid Mechanics

3D printing, Mass transfer, Electrochemistry,

Introduction

In recent years, a renewed interest in electrolyzers has emerged. They are expected to play a pivotal role in enabling the ongoing global energy transition, as they are able to directly convert electricity into chemical energy. Moreover, the process can be done cleanly if green energy is used, thereby opening up the way to a sustainable chemical industry.

A key property of an electrolyzer is its mass transfer performance. A high mass transfer performance indicates that the reactants can quickly reach the electrode, in this way enabling faster reactions and higher currents. Typically, mass transfer is expressed as a Sherwood-Reynolds correlation. In the past decades, many such correlations have been established [1-5], but there is a large variance in the reported mass transfer performance. For empty parallel plate electrolyzers, the difference can be up to an order of magnitude depending on the configuration and specific design choices that were used, such as e.g. the design of the inlet [1]. This complicates the comparison of results between them. Moreover, the importance of certain mass transfer enhancing effects depends on the scale. Small-scale electrolyzers for instance will be affected more by inlet effects than large scale cells. Therefore, when results from a small cell are extrapolated to a larger electrolyzer, significantly over- or underestimations can occur if these scaling effects are not considered.

In order to increase our understanding of mass transfer in electrolyzers more configurations need to be tested. Therein lies another complication since most of the cells described in the literature were built in-house or produced decades ago, resulting in them no longer being available for present-day research. For new research, it can therefore be difficult to find a suitable cell with known mass transfer behavior. Building new ones is not straightforward either, as it requires design work and complex machining. A solution to this problem is to 3D print electrolyzers, as it allows the quick construction of numerous prototypes.

The purpose of this work is to carry out a systematic investigation into electrolyzer mass transfer performance. 3D printed parallel plate electrolyzers are used to investigate the effects of different inlet designs, inlet lengths, and turbulence promoters and results are compared to previous work.

Theory

Measuring mass transfer

The limiting current density method is often used to determine the mass transfer performance of electrolyzers. [6-7] Typically, this involves reversible redox couples such as hexacyanoferrate or hexachloroiridate, for which the rate of reaction is limited by mass transfer at sufficient overpotential [8-10]. The limiting current is related to the Sherwood number as shown in eq. 1.

$$Sh = \frac{d_H}{D} \cdot k_{LS} = \frac{d_H}{D} \cdot \frac{i_{A,lim}}{n F C_{bulk}} \text{eq.1}$$

To understand how mass transfer occurs in electrolyzers it is important to realize that there are two different boundary layers (see figure 1). The first, is the hydrodynamic boundary layer which is the region where the velocity of the flow is lower due to friction with the wall. The second is the diffusive boundary layer, which is where the concentration of reactant species is lower due to the reaction at the electrode surface. In liquids the diffusive boundary layer is much thinner than the hydrodynamic boundary layer, since liquid diffusion coefficients are typically at least a factor 1000 smaller than liquid viscosities. Moreover, the hydrodynamic and diffusive boundaries do not necessarily develop simultaneously. For instance, if an inert section of wall

precedes the electrode, then the flow can be hydrodynamically developed before the diffusive boundary layer begins to form. Essentially, there are three distinct situations:

1. Hydrodynamically and diffusively developing flow
2. Hydrodynamically developed, but diffusively developing flow
3. Hydrodynamically and diffusively developed flow

[FIGURE 1]

Situation A is most common in electrolyzers, where the electrode typically starts directly after the inlet. Situation B occurs when a certain entrance length without electrodes is used in which the flow is allowed to develop before reaching the electrodes. Situation C only occurs after a certain length of electrode and can therefore only be seen in the downstream segments of a segmented electrode.

The distance required for a flow to reach fully developed conditions is known as the hydrodynamic entrance length. More specifically it is defined as the length needed for the centerline velocity to reach 99% of its fully developed value. In laminar flow, the entrance length depends on the Reynolds number as shown in eq. 2.

$$L_{\text{entry}} = \Phi d_h \text{Re} \quad \text{eq. 2}$$

Where Φ is a parameter that depends on the geometry. For a rectangular channel it is nonlinearly dependent on the aspect ratio of the cross-section γ' . [11] Table 1 lists the six values Han established. [11]

[TABLE 1]

To obtain fully developed turbulent flow, a hydrodynamic entrance length is required that is 50 hydraulic diameters d_H long, regardless of the flowrate [12].

In figure 2 the current in a typical mass transfer experiment is shown. In such an experiment the flow is turned on prior to the potential, giving the hydrodynamic boundary layer time to develop. When the potential is applied (at $t=0$), a current appears and quickly trends toward a stable value that is determined by the thickness of the diffusive boundary layer. The high initial current is due to the development of this layer. At most flowrates, the reaction is fully limited by mass transfer from the bulk after at most 7 seconds. At low flow rates (20 L/h and 30 L/h), it takes several seconds longer for the diffusive boundary layer to develop. This is because at lower flow rates the diffusive boundary layer is thicker and therefore there is more reactant present in this layer.

[FIGURE 2]

Mass transfer in hydrodynamically developed flow

In a perfectly laminar flow, with a perfectly hydrodynamically developed flow, the mass transfer coefficient between parallel plates in a rectangular channel can be described by a theoretical Leveque-type equation, eq. 3a [12]. Here, γ is the aspect ratio of the electrode: B/L . In the work of Ong and Pickett no significant effect has been found of the developing diffusive layer on the rate of mass transfer in laminar flow. As a consequence, eq.3a is valid for both short and long electrodes. [12-13]

$$Sh = 1.467 \left(\frac{2}{1+\gamma} \right)^{0.33} (\text{Re Sc} \frac{d_H}{L})^{0.33} \quad \text{eq.3a}$$

In some publications an alternative correlation is reported in the form of eq.3b. [1, 13-14]. This correlation is based on a best fit of the experimental data obtained by Ong and Pickett [13]. The difference with eq. 3a has been explained as being the result of electro-organic absorption of m-nitrobenzene. [12] These electro-organic impurities poison the electrode surface resulting in lower than expected mass transfer, especially at higher flowrates. Similar poisoning behavior is seen for the hexacyanoferrate redox couple. [8-10]

$$Sh = 2.54 (\text{Re Sc} \frac{d_H}{L})^{0.296} \quad \text{eq.3b}$$

The correlations for a perfectly developed turbulent regime are based on analogies between momentum and mass transfer. Many different analogies exist, both theoretical (Prandtl, Von Karman) and empirical (Chilton-Colburn, Lin-Koulton-Putnam, Deissler, Vieth-Porter-Sherwood, Wasan-Wilke, Dittus-Boelter). Most of these analogies can be rewritten in the form of $Sh \sim Re^b Sc^c$, with varying powers of Re and Sc. In the work of Ong, the Chilton-Colburn analogy is found to be most representative of their dataset [12] :

$$Sh = \frac{f}{2} Re Sc^{0.33} \text{ eq. 4a}$$

This analogy sets c at a value of 0.33 and uses the friction factor f. Typically, f is determined by a further correlation to the Reynolds number, i.e.: $f \sim a^* Re^{b^*}$. In some references, eq.4a is written using the J-factor instead of the friction factor. [12-13, 15] The M subscript denotes mass transfer. The J-factor is equal to $f/2$:

$$Sh = J_M Re Sc^{0.33} \text{ eq. 4b}$$

For fully developed turbulent flow, Pickett and Ong determined two separate correlations for the J-factor: one for short electrodes with $Le = L/d_H < 10$, and another for long electrodes with $Le = L/d_H > 12$ [13]. Filled into eq.4b, these result in eq.5a and eq.5b. For short electrodes (eq.5a) the Le number was introduced as a variable, because mass transfer depended significantly on their relative length. Hence eq. 5a corresponds to a situation that is hydrodynamically developed, diffusively developing, whereas eq. 5b corresponds to a hydrodynamically and diffusively developed situation.

$$Le < 10 : \quad Sh = 0.125 Re^{0.66} Sc^{0.33} Le^{-0.25} \text{ eq. 5a}$$

$$Le > 12 : \quad Sh = 0.023 Re^{0.8} Sc^{0.33} \text{ eq. 5b}$$

Experimental

In this work, a 3D-printed electrolyzer was used. The structural parts of the 3D-printed electrolyzer were printed both in-house and externally. In the former case, a MakerGear M3-ID or a Prusa MK3S was used. In both printers, PETG was extruded during the fused filament fabrication process. In the latter case parts were ordered from the 3D printing company ZiggZagg, who used the multi jet fusion of Nylon. The gaskets were printed in-house using TPU filament Ninjatek-Ninjaflex and the MakerGear M3-ID. The electrolyzer is shown in figure 3 and consisted of exchangeable inlets and electrode assemblies. In table 2 the characteristic dimensions of the electrolyzer are shown. The electrode assembly was built by affixing a 100x50mm nickel plate to a printed substrate using epoxy resin. The electrical connection was provided by two wires soldered to the backside of the nickel plate on one end, and 2 banana plugs on the other end.

[FIGURE 3]

[TABLE 2]

[FIGURE 4]

For the 3D-printed electrolyzer, three different inlets were used in this work: a tube inlet, a conic inlet, and a divider inlet (see figure 4). Additionally, it was possible to add a calming section with printed extender pieces that were either 100 mm, 150 mm or 200 mm long, thereby increasing the hydrodynamic entrance length. These extender pieces contained an empty rectangular channel with the same cross-section as the part containing the electrodes. Measurements with longer calming sections of 300 mm and 550 mm were carried out by using multiple extender pieces.

Turbulence promoters could be inserted into the channel of the electrolyzers. Four different designs were tested: tube grid, large gyroid, medium gyroid and small gyroid (figure 5). The designs were printed in a small form (100x40 mm) built to fit the non-extended electrolyzer and a longer 250x40 mm form meant to fit a channel extended by 150 mm (figure 6).

[FIGURE 5]

[FIGURE 6]

The setup consisted of an electrolyte vessel connected via a gear pump to the printed electrolyzer and is schematically shown in figure 7. A variable area flow meter (Swagelok) was used to measure the flow rate. The pressure drop was measured by means of an 800 mm tall U-tube filled with water. The electrolyte vessel was continuously flushed with nitrogen. A water lock was used to prevent backmixing of atmospheric oxygen. The concentration of the oxidant (hexachloroiridate(IV)) was tracked throughout the experiment using an inline UV-VIS flow cell (Avantes).

[FIGURE 7]

The hexachloroiridate(IV)/hexachloroiridate(III) redox couple was used for the limiting current density measurements. The electrolyte consisted of 0.5 mM potassium hexachloroiridate(IV) (>99.99% from Merck/Sigma Aldrich) and 1.0 mM hexachloroiridate(III) (>99.9% from Merck/Sigma Aldrich) in a solution of 0.5 M KNO_3 (>99% from VWR Chemicals), containing 0.1 M of potassium acetate pH 4 buffer (made from >99% potassium acetate and >99% acetic acid from VWR Chemicals). More background on the performance of the hexachloroiridate redox couple can be found in previous work [16]. A list of the electrolyte properties is available in table 3.

[TABLE 3]

Before the experiments, the electrodes were pretreated following the recommendations of Szanto et al. [9] The procedure consisted of polishing the electrodes using felt paper and a descending series of alumina particles (namely 1.0 μm , 0.3 μm and 0.05 μm), followed by two times 15 minutes sonication and 15 minutes of hydrogen evolution in 0.5 M KOH solution. The setup was then thoroughly rinsed with a solution containing 0.1 M pH 4 acetate buffer and 0.5 M KNO_3 . During this time, a baseline measurement of the UV-VIS probe was taken. After this, the setup was drained, flushed with nitrogen and the hexachloroiridate electrolyte was added. For another 15 minutes, nitrogen was bubbled through the electrolyte vessel to remove dissolved oxygen from the solution.

Chronoamperometry experiments were performed in order to determine the limiting current density. The procedure was as follows: First, the gear pump was set in motion to produce the desired flow rate. Then, a cell potential of -0.8 V was applied and a waiting time of at least 7 seconds was implemented in order to reach a steady state situation. The limiting current was determined from the average of 30 data points measured over a period of 3 seconds after the current had stabilized.

In our work we record all current data after 7 seconds. Since for low flow rates (see figure 2) the current has not always completely stabilized after 7 seconds, the Sherwood numbers obtained at lower flow rates (and hence lower Reynolds numbers) may be overestimated slightly in our work.

Results and discussion

Overview of mass transfer correlations in electrolyzers

Numerous experimental studies with the aim of establishing mass transfer correlations have been reported. [1-5,12-14,18-37] Table 4 and figure 8 list a selection of these correlations. Generally, they are of the form $Sh = a Re^b Sc^c Le^{-d}$. For these, the Schmidt power is typically set to 0.33 which is in accordance with the Chilton-Colburn analogy. In rare cases, the relative length of the electrode $Le = L/d_H$ is taken into consideration, denoted by a non-zero d coefficient. Typically, this is done when a dependency on the electrode length could be confirmed. However, most studies do not vary the electrode length which could be a reason for not including this parameter in their investigation.

[TABLE 4]

[FIGURE 8]

Generally, literature correlations show Reynolds powers between 0.6 and 0.8, which is an indication of a turbulent regime. The correlations established by Pickett et al. [13] for developed turbulent flow also follow this trend: for short electrodes the power is 0.66, for long electrodes it is 0.8. Interestingly, most electrolyzers appear turbulent long before the expected transition point of $Re = 2000$. This could be due to several reasons, such as surface roughness, turbulence caused by the inlet or even imperfections in the cell itself.

The rate of mass transfer varies significantly depending on the electrolyzer type that is used. In for instance the UA16.15 a rate of mass transfer is found that is nearly 10 times higher than the correlations established by Pickett et al. In other electrolyzers, increased mass transfer is also observed, though the effect is less extreme. There are several possible explanations for this difference. Firstly, most electrolyzers do not use calming sections and are therefore not operating in developed flow conditions, unlike the one used in the work of Pickett et al. [13] Secondly, significant turbulence is generated by the inlets into the channel, which varies between designs. Thirdly, the design of the channel could be of some importance: square, rectangular and even circular parallel plates have been used in literature. [23,28,35] Finally, within the same electrolyzer variations in performance may exist as a result of small differences in the way the cell is reassembled after maintenance. For instance, with a filter-press design, the layers of gaskets spacers and electrodes may be stacked in slight misalignment. This in turn would result in more mass transfer than expected due to extra protrusions of these misaligned components into the channel. In turbulent flow the surface roughness is also of importance. [29]

3D printed electrolyzer with different inlets

To systematically investigate inlet effects, we developed a modular 3D printed electrolyzer with exchangeable inlets. Three types of inlets were used: a conic inlet, a tube inlet and a divider type inlet (shown in figure 4). Results for these inlets are shown in figure 9. All three inlets produce higher rates of mass transfer than expected from the predictions by Pickett et al (eq 2.). Furthermore, for the conic and divider type inlet, a region with a smaller slope and a ($Re < 300$) region with a larger slope ($Re > 300$) can be discerned. The tube inlet shows a large slope at all flow rates. The aforementioned regions represent laminar and turbulent flow respectively. In the laminar region, a similar performance is seen for the conic and divider inlet. Therefore, only one mass transfer correlation is established (eq.6) for both inlets in laminar flow ($Re < 300$).

$$\text{Conic, divider inlet : } Re < 300 : \quad Sh = 1.72 Re^{0.247} Sc^{0.33} \text{eq. 6}$$

Compared to eq.3a a higher rate of mass transfer is observed. This could be due to protrusions resulting from imperfections in the printed parts or the rubber seals between them. Additionally, the Reynolds power in eq.6 is 0.247 compared to the power of 0.33 in eq.3a. The likely reason for this is that the current at low flow rates is not fully stabilized, as shown in figure 2. The effect likely also contributes to the higher performance in eq.6 compared to eq.3a.

[FIGURE 9]

In the turbulent region the rate of mass transfer with the conic inlet is a factor 1.4 higher (at $Re = 1000$) compared to the divider inlet. Mass transfer with the tube inlet is a factor 2.3 higher (at $Re = 1000$) compared to the divider inlet. This difference is the result of an earlier transition to the turbulent regime, which in turn is caused by the sudden expansion of the inlet to the channel. Djati et al. [19] investigated the effect of these expansions on the rate of mass transfer in slit and tube inlets. They established a correlation using the inlet to channel cross sectional area ratio A_{in}/A_{ch} as a parameter (eq. 6). If $A_{in}/A_{ch} = 1$, no expansion occurs and the equation describes hydrodynamically developed turbulent flow comparable to equation 5a. The difference between eq.7 and eq.5a or eq.5b is small. [19]

$$Sh = 0.068 \left(\frac{A_{in}}{A_{ch}} \right)^{-0.5} Re^{0.72} Sc^{0.33} \text{eq. 7}$$

In our case, the tube inlet has an area ratio of 0.07. The divider inlet is a series of slits, with the ratio of

the area of all openings to the channel being 0.52. The conic inlet ends in the same cross-sectional area as the channel, which implies that the ratio is 1.0. Using these values, eq. 7 results in a good prediction for the divider inlet at $Re > 500$ (max deviation $< 8\%$) and to a lesser extent the tube inlet (max deviation $< 18\%$). For the conic inlet on the other hand the prediction appears to be inaccurate. This is because the ratio of 1.0 implies that there is no expansion, but expansion is occurring in the inlet. Therefore, we used the geometric mean to determine the ratio: $A_{in} = \sqrt{A_{in,0} * A_{in,1}}$, where $A_{in,0}$ is the area at the beginning of the inlet and $A_{in,1}$ the area at the end of the inlet. For the conic inlet the area ratio then becomes 0.26. With this ratio, the prediction closely matches the experimental results at $Re > 300$ (max deviation $< 6\%$)

By finding the intersect of the laminar and turbulent correlations, the Reynolds number at which the transition occurs Re_t can be determined. When combined, and solved for Re , eq.6 and eq.7 lead to eq.8, which gives Re_t as a function of the cross-sectional area ratio of the inlet to the channel.

$$Re_t = 925 \left(\frac{A_{in}}{A_{ch}} \right)^{1.06} \quad \text{eq. 8}$$

Eq. 8 predicts that the flow transition occurs at $Re_t = 223$ for the conic inlet, $Re_t = 463$ for the divider inlet and $Re_t = 56$ for the tube inlet. The transition for the conic and divider inlet are observed in figure 9. For the tube inlet Re_t is near the first datapoint of the graph and therefore the transition cannot be seen. When $A_{in}/A_{ch} = 1$, no expansion takes place and $Re_t = 925$. This is far earlier than expected from the work of Ong and Pickett [12,13], possibly due to the imperfections in the printed parts and the assembly thereof.

3D printed electrolyzer with different entrance lengths

In figure 10 the effect on mass transfer of adding a calming section between the inlet and the electrolyzer is shown. When no calming section is used, the type of inlet is important as the turbulence generated by it greatly enhances mass transfer. By adding a calming section, this effect is diminished and for a calming section of 550 mm the type of inlet no longer seems to matter. According to eq. 5 the laminar entrance length is 240 mm at the highest Reynolds number measured ($Re = 1200$). Therefore, it makes sense that an inlet well beyond this distance would no longer influence the mass transfer to the electrodes. Furthermore, the divider type inlet seems to perform similar at any length of calming section. This implies that a good inlet design can enable hydrodynamically fully developed laminar flow.

[FIGURE 10]

Despite using a 550 mm long calming section, our correlations still do not completely match the hydrodynamically fully developed laminar flow correlation established by Ong at Reynolds numbers below 500. As previously mentioned, an overestimation of mass transfer occurs at low Reynolds numbers, since the current is not fully stabilized after 7 seconds. Apart from this effect, additional experimental error is expected due to the limitations of 3D printing. A first limitation is that due to the print process imperfections may be introduced into the channel wall. These imperfections lead to increased surface roughness, which may result in higher mass transfer and an earlier transition to the turbulent regime. Secondly, because the longest dimension of a print is limited to around 200 mm, the assembly consists out of multiple smaller parts with joints between them. At these joints, minor protrusions may exist that can introduce turbulence.

3D printed electrolyzer with turbulence promoters

Often, turbulence promoters are added to parallel plate electrolyzers in order to enhance mass transfer. [1,5]. This degree of mass transfer enhancement is also widely seen in literature.[2,4-5,18,20,22,24] However, the opposite is observed in the work of Frias ferrer et al. [21], where the turbulence promoter reduces mass transfer. The difference is probably due to the design of the inlet device: the electrolyzer used by Frias-ferrer et al. [21] uses an inlet that causes high turbulence and high rates of mass transfer. A turbulence promoter added to this environment calms down the highly turbulent inlet flow.

In figure 11 the performance is shown of a selection of turbulence promoters in the 3D printed electrolyzer, with and without a 150 mm calming section. The promoters fill the entire empty channel in both configurations (see figure 6). In either case, the turbulence promoters increase mass transfer significantly. The

enhancement at $Re = 1000$ varies between a factor 2.3 and 2.8 without a calming section and between a factor 1.8 and 4.0 with the calming section. Interestingly the variation in enhancement is larger when a calming section is used, despite having similar empty channel performance. A possible explanation is that a secondary inlet effect occurs when the flow first hits the turbulence promoter. In the first few centimeters of the promoter this could result in higher than expected turbulence, which would initially increase the rate of mass transfer. This would explain why promoters such as the tube promoter perform better in the cell without calming section. However, with the small gyroid promoter the opposite effect is observed, as it performs better with a calming section than without. Here it is possible that the divider type inlet is channeling the flow into certain paths in the structure of the promoter, resulting in localized spots with little flow and mass transfer. For the cell without calming section, this would result in lower average mass transfer. With a calming section, this flow channeling is smoothed out before the electrode section is reached and therefore the effect of the localized dead volumes is not seen.

[FIGURE 11]

Pressure drop in the printed cell

The pressure drop of the 3D printed electrolyzer without turbulence promoters was small and varied between 26 ± 2 mbar and 38 ± 2 mbar at Reynolds 1000 depending on the configuration (see also appendix figure A1). The highest pressure drop was found for the tube inlet, the lowest for the divider inlet. Since these differences are small, it is likely that their accuracy is strongly affected by the imperfections in the print and the gasket joints between components of the cell. Furthermore, because the pressure drop was measured across the entire electrolyzer, it may be possible that factors such as the placement of the external tubing or the tightness of the fittings lead to further inaccuracy. Turbulence promoters did not significantly affect the pressure drop. For the divider inlet without calming section, the pressure drop at Reynolds 1000 was 27 ± 2 mbar for every promoter (see also appendix figure A2). In the cell with divider inlet and a 150 mm calming section, the pressure drop varied between 27 ± 2 mbar and 35 ± 2 mbar for the promoters compared to 22 ± 2 mbar in the empty channel. Generally, a trend exists wherein the better performing turbulence promoters cause a higher pressure drop, though the difference is small.

Conclusion

The different design choices made in the construction of an electrolyzer greatly affect the mass transfer performance. Between the electrolyzers found in literature, up to a factor 10 difference is observed (see figure 8). This variation is the result of several different geometric design choices in the electrolyzer. Using a 3D printed electrolyzer, we were able to investigate the effect of some of these choices.

Depending on the type of inlet that was used, up to a factor 2.2 difference in Sherwood numbers was seen. Furthermore, an earlier transition to the turbulent regime was found. The tube inlet already produced turbulent flow at $Re = 65$, the conic and divider inlet transitioned around $Re = 300$. The higher than expected mass transfer is due to the sudden expansion of the inlet to the channel. In turbulent flow, the correlation by Djati et al. predicts mass transfer fairly well. [19] This correlation uses the ratio of cross-sectional area of the inlet and channel as parameter to predict the magnitude of expansion turbulence. In the conic inlet, the cross-sectional area varies throughout the inlet and this was accounted for by using the geometric mean cross-sectional area. The correlation deviated from the experimental results by $<18\%$ for the tube inlet, $<8\%$ for the divider inlet and $<6\%$ for the conic inlet.

The addition of a calming section minimized these effects. With a calming section of 550 mm, the type of inlet no longer seemed to affect the rate of mass transfer. This length is over twice the predicted hydrodynamic entrance length of 240 mm at $Re = 1200$ (based on eq. 5). Therefore, it is reasonable to assume that the flow is fully developed and that the inlets no longer matter. Despite this, our results did not completely match the correlations for hydrodynamically developed flow established by Ong. [12-13] This is likely the result

of the limitations of 3D printing, as this process can result in imperfections in the printed parts that may disturb the flow.

Turbulence promoters generally lead to an enhancement of mass transfer. The presence of a calming section significantly changed the enhancement effect of the promoters. Without calming section, most of our promoters resulted in comparable Sherwood numbers, whereas with an entrance length a larger variance in performance was found. Inlet turbulence therefore greatly influences the effect of a turbulence promoter.

The pressure drop was measured for the different configurations of inlet length, inlet type and turbulence promoters. Overall, only very small differences between each configuration were observed (in the order of 100 pascal). Though the difference is marginal, it appears that higher pressure drops result in higher mass transfer rates.

Mass transfer in electrolyzers can be significantly enhanced by turbulence promoters or turbulence causing inlets. The added pressure drop for these is minimal, which implies that large performance increases can be achieved for little extra pumping costs. However, due diligence must be taken in extrapolating results from the lab-scale to the industrial scale. Since the importance of the inlet effect diminishes as the electrolyzer scales up, mass transfer may be slower than expected from the lab-scale. As we have shown, a good inlet design or a calming section can reduce inlet turbulence in smaller electrolyzers, so that they are more representative of their larger counterparts.

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Notation

γ	Electrode aspect ratio B/L
ν	Kinematic viscosity
ρ	Density of the electrolyte
Φ	Geometry parameter for laminar entry length
\mathbf{A}	Electrode area
\mathbf{A}_{ch}	Cross-sectional area of the channel
\mathbf{A}_{in}	Cross-sectional area of the inlet
\mathbf{B}	Electrode width (breadth)
$\mathbf{C}_{(\text{III})}$	Concentration of hexachloroiridate(III)
$\mathbf{C}_{(\text{IV})}$	Concentration of hexachloroiridate(IV)
\mathbf{C}_{bulk}	Bulk concentration of the reacting species
\mathbf{D}	Diffusion Coefficient
\mathbf{d}_{H}	Hydraulic Diameter $2BS/(B+S)$
\mathbf{F}	Faraday's number, i.e. 76485 C/mol
\mathbf{f}	Friction factor
$\mathbf{i}_{\text{A,lim}}$	Limiting current density
\mathbf{J}_{M}	J-factor for mass transfer (Chilton-Colburn)
\mathbf{k}_{LS}	Liquid-Solid Mass transfer coefficient
\mathbf{L}	Electrode length
$\mathbf{L}_{\text{entry}}$	Hydrodynamic Entry Length
\mathbf{Le}	Length number L/d_{H}

γ	Electrode aspect ratio B/L
n	Number of electrons exchanged
Re	Reynolds number $v_0 d_H / \nu$
S	Electrode spacing
Sc	Schmidth number ν / D
Sh	Sherwood number $k_{LS} d_H / D$
T	Temperature
v_0	Flow velocity over the electrode

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