Supplemental information

A new perspective crosslinks the electrochemistry and other research fields: beyond electrochemical reactor

When exploring the application of electrochemical O_2 removal technology in the field of food preservation, comparing its energy consumption with that of traditional N_2 displacement O_2 removal methods became a challenge. This challenge mainly stemmed from the lack of directly related studies, making it difficult to precisely compare their energy consumption. Despite these limitations, we conducted direct measurements of the energy consumption for the N_2 displacement O_2 removal strategy and made rough estimates for the energy consumption of the electrochemical O_2 removal method, allowing us to offer a preliminary comparison. We hope that this comparison illustrates the potential application prospects of electrochemical O_2 removal technology in food preservation, encouraging researchers in the field of electrochemistry to further explore and expand upon the research in this area.

We conducted a series of experiments to measure the time and energy consumption of O_2 removal using a PSA nitrogen (N_2) generator. In the experimental setup, a 5L sealed chamber was prepared and was continuously fed N_2 produced by the PSA device into the chamber at a flow rate of 1L/min to reduce the O_2 concentration inside. An O_2 sensor and a power meter were applied to record the time and energy consumed to achieve different O_2 concentrations. Figure 1 demonstrates the correlation between the decrease in O_2 concentration and the increase in energy consumption by the PSA device. It is particularly noteworthy that as the O_2 concentration falls below 10%, the energy required for O_2 removal increase sharply. Furthermore, when the concentration drops below 5%, this growth trend undergoes a significant exponential acceleration, indicating a rapid decrease in O_2 removal efficiency. These results clearly show that the efficiency of O_2 removal via N_2 displacement diminishes dramatically with O_2 concentrations decreased, leading to significantly elevated energy consumption. In situations where extremely low O_2 concentration is required, the diminished concentration gradient between the gases increase difficulty of the displacement process, leading to a marked reduction in O_2 removal efficiency.

In the analysis of energy consumption for the electrochemical O_2 removal process, lowering O_2 levels is facilitated by the electrochemical ORR. The energy required for this process can be estimated under specific simulated conditions. A system of 5L chamber linked with an electrochemical O_2 removal reactor is designed, as illustrated in schematic diagram (Fig. 3b). This design allows gas from the sealed chamber to be introduced into the electrochemical O_2 removal reactor, where it undergoes deoxygenation through the ORR process. The residual gas is then recycled back into the sealed chamber, thus establishing an efficient cyclic O_2 removal system. A pressure balance valve is quipped on the sealed chamber to maintain consistent pressure inside and outside. Below is the equation for calculating the electrochemical O_2 removal process: For a 5L sealed environment, the goal is to reduce the O_2 concentration in the atmosphere from 21% to various target concentrations, represented by *x*.

$$E_{total} = (5*(100\%-x)/(100\%-21\%)-5)/V_m \times n \times F \times E/3600 \qquad (1)$$

In the equation above, E_{total} represents the energy consumption required for O_2 removal, measured in Wh; x is the target O_2 concentration; V_m is the molar volume of gas, which is 24.5 L/mol at 25 °C and 101 kPa; the Faraday constant F =96485C/mol; E is the applied voltage, assumed to be 1.0 V; *n* is the number of electron transfers in the ORR reaction.

From the energy consumption formula for the electrochemical removal of O_2, it's evident that the energy required for the process adheres to a linear relationship, with the energy demand being directly proportional to the volume of O_2 to be eliminated. This insight reveals that the efficiency of electrochemical O_2 removal remains unaffected by decreases in the target O_2 concentration levels. Hence, even in scenarios where exceedingly low O_2 concentrations are desired, the electrochemical O2 removal method retains its high efficiency, without incurring a significant increase in energy consumption because of diminished concentration gradients.

Given a 4-electron transfer condition, applying the above equation (1) yields calculated energy consumptions for achieving target O_2 levels of 15%, 10%, 5%, 4%, 3%, 2%, and 1% at 1.66 Wh, 3.05 Wh, 4.43 Wh, 4.71 Wh, 4.99 Wh, 5.26 Wh, and 5.54 Wh, respectively. For a 2-electron transfer condition, the corresponding energy consumption is exactly half of that calculated under the 4-electron conditions.

Fig. 3c clearly demonstrates the significant difference in energy consumption between O_2 removal of electrochemical device and N_2 displacement by PSA device. Particularly, when the target O_2 concentration is reduced to 1%, the energy consumption required by the PSA device is as high as 125.6 Wh, whereas the estimated energy consumption for electrochemical device is about 5.54 Wh, only 4.4% of the former. This comparison underscores the substantial potential of electrochemical O_2 removal in boosting efficiency and conserving energy.