Carbon dioxide gas delivery to thin-film aqueous systems via hollow fiber membranes

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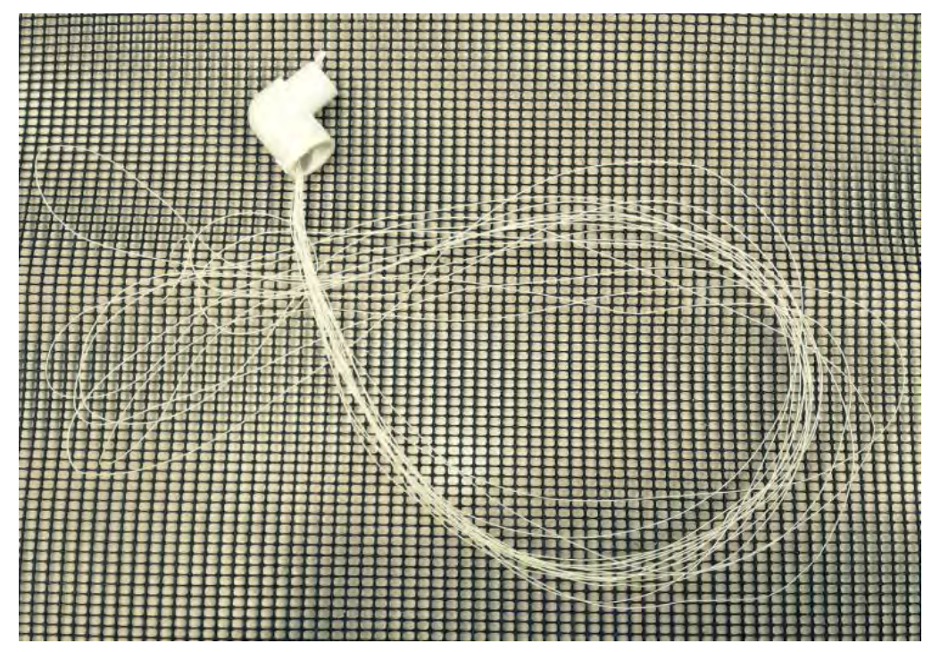
THE PROBLEM

Carbon dioxide addition has shown to enhance algae growth in closed systems such as photobioreactors [1]. However, little research has been performed on its addition to open systems such as raceway ponds and Algal Turf Scrubbers™, where flue gas could be used as a carbon dioxide-rich feed [2]. Hollow fiber membranes have great potential for application in these open systems due to their large surface area, small pore sizes, and ability to implement lower gas pressures with the same productivity [3]. They have been used in other gas-liquid contacting applications such as carbonation of beverages, protein extraction, VOC removal [4].

THE PROJECT

Carbon dioxide gas delivery was tested via three methods: open tube, commercial diffuser, and hollow fiber membranes. The hollow fiber membranes were folded in half and potted with epoxy in a PVC elbow (see below). Gas was delivered by a compressed gas cylinder, at a flow rate of 0.1 liters per minute to an Isotemp water bath of DI water at depths of 1.5”, 3”, and 5”. The pH values of the water were recorded over time and the carbonic dissociation relationships were used to determine the carbon dioxide concentration at a given time. Temperature was also varied at a water depth of 1.5”.



Evapoporometry, a technique developed by Krantz [5], was used to determine the average pore size of the hollow fiber membranes. This technique operates upon the principal that a volatile wetting liquid will evaporate from a membrane progressing from largest to smallest pores due to the relationship between the pore radius and the instantaneous vapor pressure. The membranes were glued to the bottom of a Plexiglas container and isopropyl alcohol (IPA) was used to submerge the membranes. The container was placed on a microbalance and the evaporation rate of the IPA was measured over time using a data acquisition software.

A model for bubble size prediction based on orifice diameter developed by Ramakrishnan [6] was used to predict the bubble size produced by the hollow fiber membranes. These values were used in determining some parameters in the mass transfer model that was developed for the hollow fiber membranes.

RESULTS

The results for the carbon dioxide concentration calculated from the pH readings for all delivery mechanisms and depths tested are shown in Figure 1. This data shows that the hollow fiber membranes are far superior at all depths tested, especially at the shallowest depth where they delivered 60 times the amount of carbon to the system than open tube bubbling, and 6 times the amount of carbon than the commercial diffuser.

Evapoporometry was conducted in three trials on the hollow fiber membranes and the results, given in Figure 2, show that the average pore diameter is 27 nm with a standard deviation of 13 nm. This data also shows that the membranes have possible defects above 80 nm. This pore diameter was used in the Ramakrishnan model for bubble size prediction.

A mass transfer model for the hollow fiber membranes was developed and fit the experimental data well, shown in Figure 3. The model used an overall mass transfer coefficient, KL, of carbon dioxide into the media determined from the individual mass transfer coefficients in the liquid phase, membrane and gas phase. However, due to the low solubility of carbon dioxide in water, Henry’s constant is large making the resistances of the gas phase and membrane material negligible. During experimentation it was noticed that the bubbles would remain on the surface of the hollow fiber membranes for an extended time until they coalesced with adjacent bubbles and rose to the surface. Due to this observation, the mass transfer coefficient was broken down into two terms: one for the contribution for the bubbles that remain on the membrane surface and another for the contribution of the bubbles rising through the solution. By doing a mass balance on the carbon dioxide in the system, breaking down the mass transfer coefficient into two terms, and evaluating the equation with the measured parameters, the following model was developed:

$$C = C^{*}(1\text{-}e^{\frac{-K_L At}{V}})$$

where

$$K_L = K_{L-HFM}\frac{A_{HFM}}{V} + K_{L-liq}\frac{A_{liq}}{V}$$

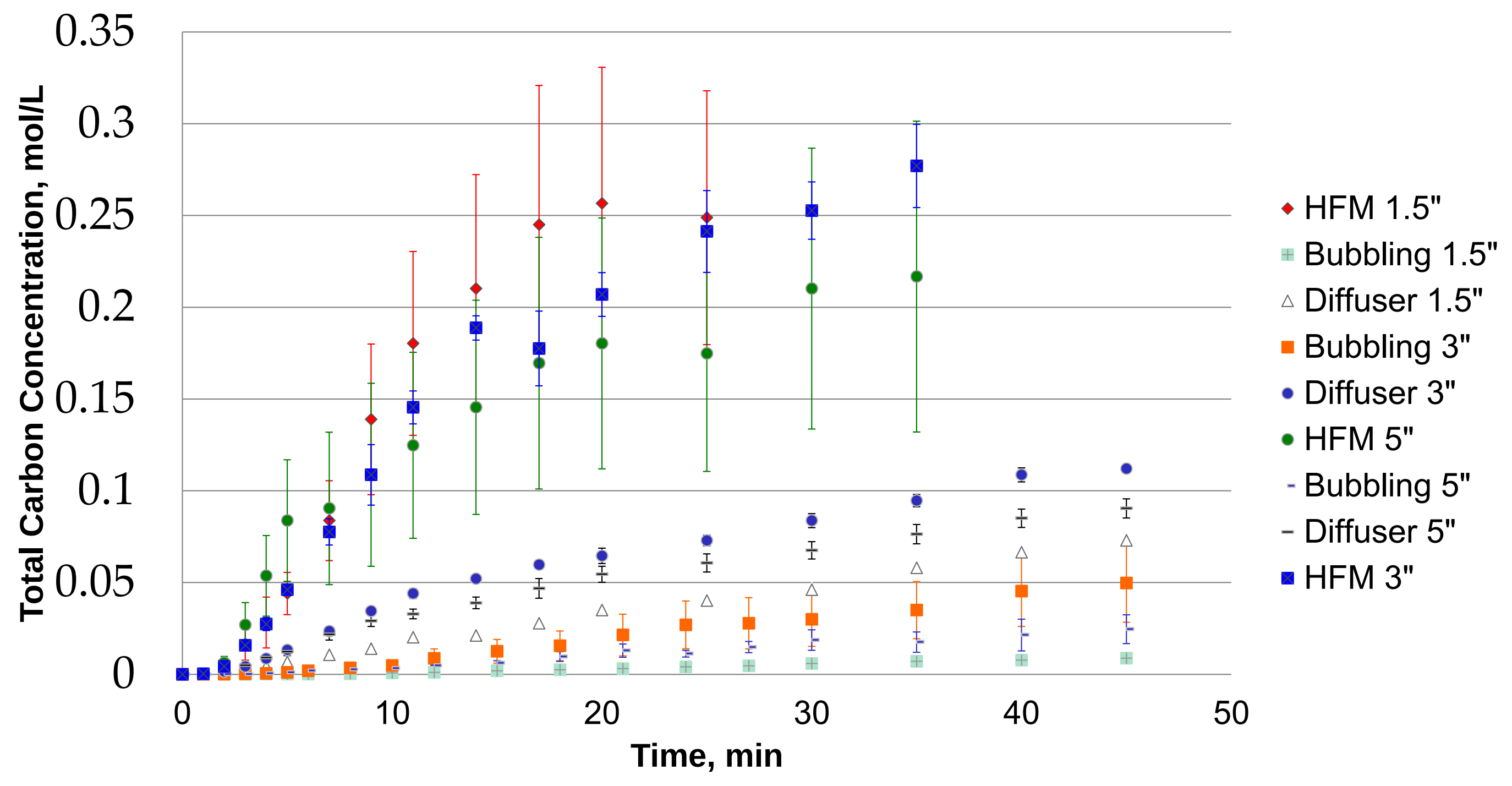


Figure 1 Carbon dioxide concentration overtime for the hollow fiber membranes, open tube, and porous diffuser at 20°C and three different depths..

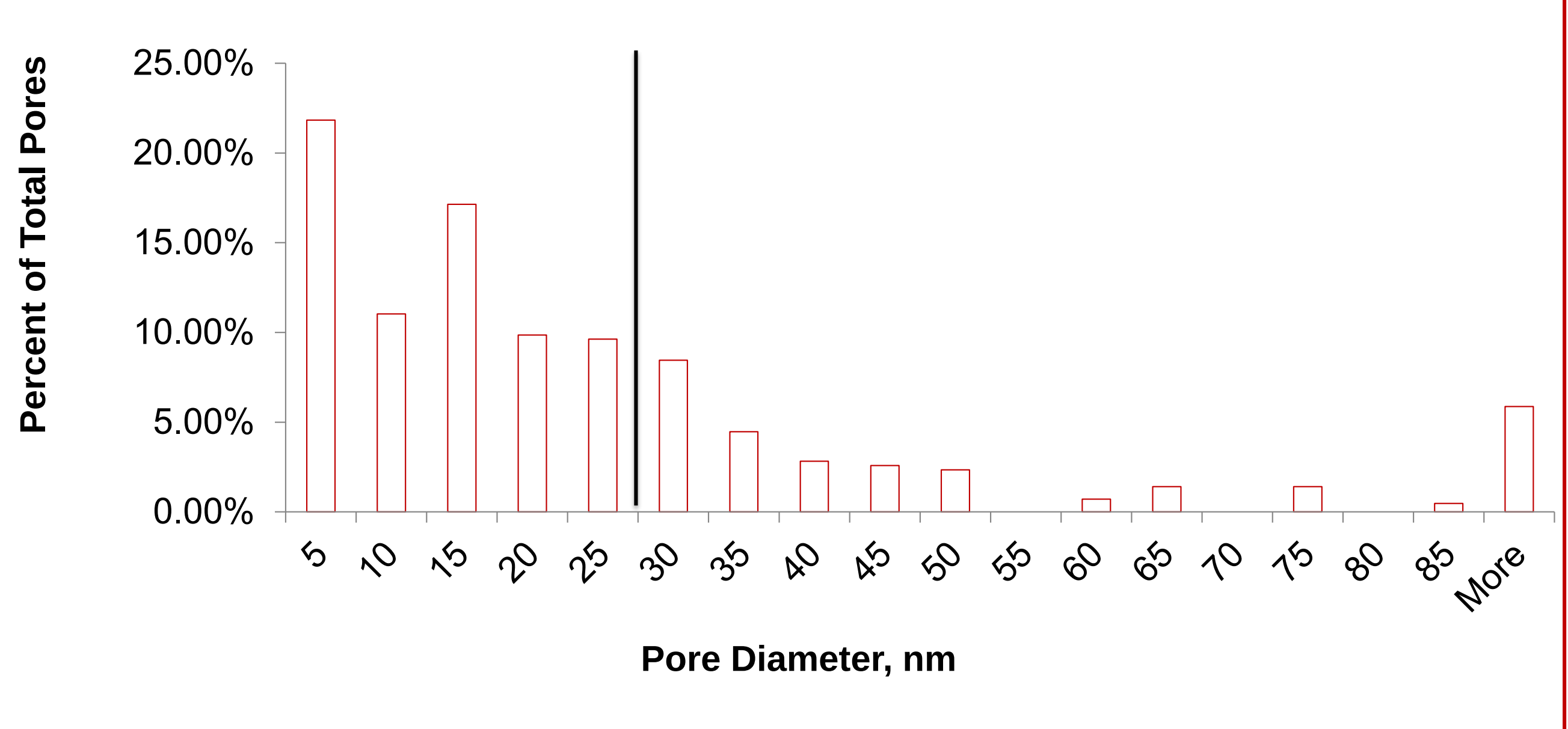


Figure 2 The pore size distribution of the hollow fiber membranes as determined by evapoporometry. The solid black line represents the average pore diameter.

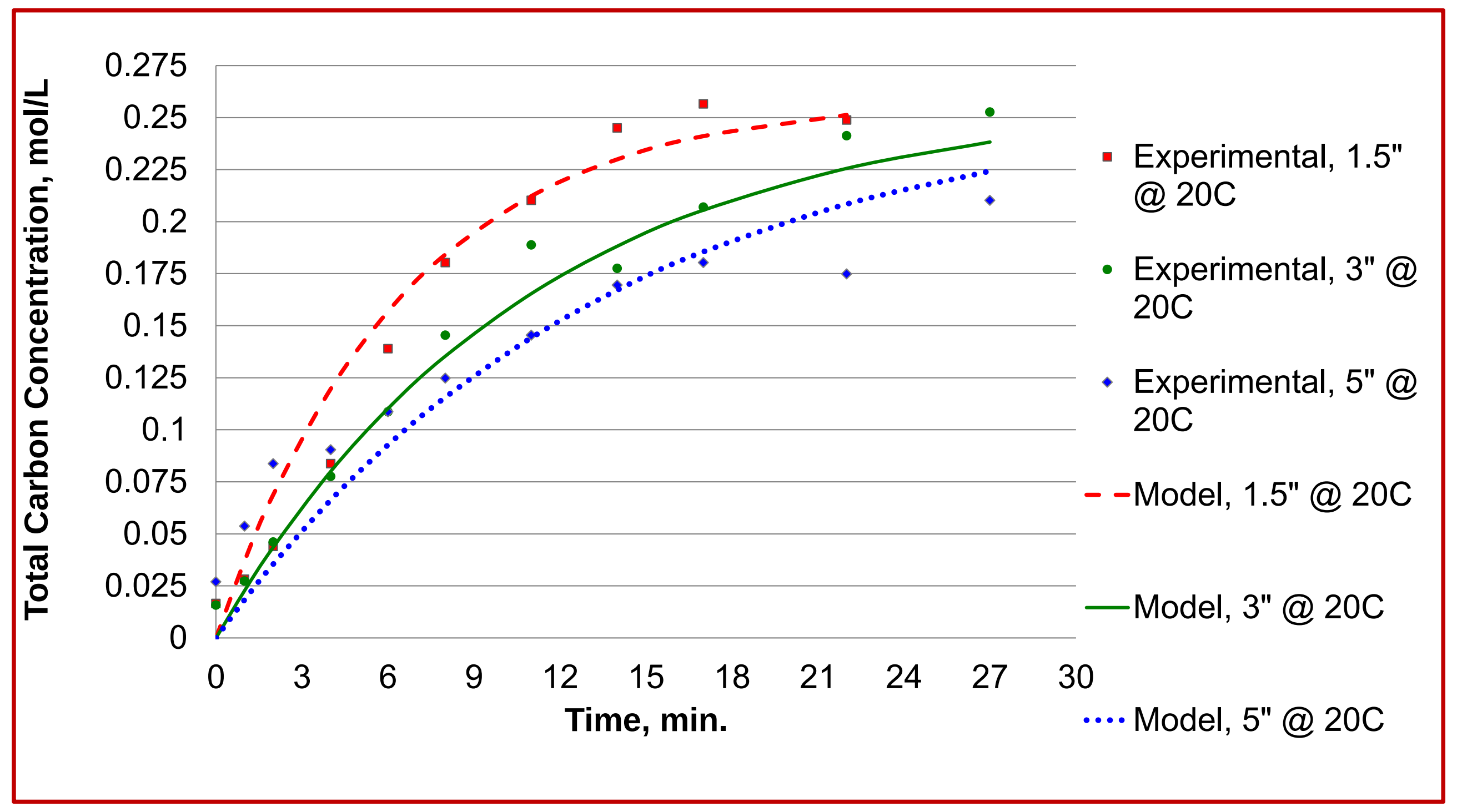


Figure 3 Comparison of the two parameter mass transfer model and experimental data for hollow fiber membranes at 20°C and three different depths.

CONCLUSIONS

Gas delivery to a thin-film aqueous system was tested using three different gas delivery devices: hollow fiber membranes, an open tube, and a porous diffuser.

The ability for these devices to deliver carbon dioxide to the system was tested at depths of 1.5 inches, 3 inches, and 5 inches. The hollow fiber membranes were found to be the most effective method for introducing carbon dioxide to the system at all depths tested, especially at the lowest depth. At the lowest depth, the hollow fiber membranes gained a key advantage over the other gas delivery mechanisms as the hydrophobicity of the membranes caused the bubbles to remain on the surface of the membrane before rising through the liquid. This allowed for a longer retention time of the bubbles in the liquid. Another key advantage of the hollow fiber membranes is the ability to spread the membrane throughout the entirety of the bottom of the water bath, rather than having a single point of delivery into the bath. Additionally, the microbubbles produced by the hollow fiber membranes have a much larger surface area than the bubbles produced by the open tube and porous diffuser. This large surface area means that there is a higher gas-liquid interfacial area that can allow for greater mass transfer. A mass transfer model was developed to describe the system with the mass transfer coefficient broken down into two parts: the mass transfer attributed to the bubbles at the surface of the membrane and the mass transfer attributed to the bubbles rising through the liquid. This model accurately described this system for low water depths and, therefore, is applicable to thin-film aqueous systems such as algal raceways and algae turf scrubbers.

SUSTAINABILITY

This research involves promoting the sustainable design and operation of algal growth systems for their primary use in the production of biofuel. Sustainable design and operation requires careful understanding of the interconnection and value in the economics, environment, society, and culture that affect and are affected by the process. Currently, the major drawback for the production of biofuels from algae is the difficulty in making the process more economically feasible than the currently available non-renewable and renewable energy resources. This research hopes to overcome this problem by enhancing the algae growth through the addition of carbon dioxide, a product consumed by the algae. This would increase the biomass that could be produced in a given time period. Furthermore, this research could also have large positive impacts on the environment. The carbon dioxide delivered to these systems could come from industrial flue gas. This would result in a decrease in carbon dioxide emissions and the algae could act as a filter for heavy metals and other chemicals that are typically carried out with flue gas. Additionally, the ability to produce a renewable energy resource can reduce the demands on non-renewable energy resources, such as oil and natural gas that not only have negative impacts on the environment but also are a source of social and political conflict around the world due to their uneven distribution. By increasing algae production through carbon dioxide delivery from industrial flue gas, biofuels can be produced in a sustainable manner that promotes positive economic, environmental, social, and cultural outcomes.

CITATIONS

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