FERMENTATION AND OXYGEN TRANSFER IN MICROGRAVITY

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ABSTRACT

The need for high rate oxygen transfer in microgravity for a CELSS environment offers a number of unique difficulties and challenges. The use of a phase separated bioreactor appears to provide a way of overcoming these problems resulting in a system capable of providing high cell densities with rapid fermentation rates. Some of the key design elements are discussed.

PURPOSE

Biological processing and thus fermentation is likely to take place in space under two main driving forces. Firstly, as unique biological effects are uncovered in microgravity, and as novel bioseparation processes particular to the microgravity environment are developed, it is likely that some fermentation, for example on the space station, will become appropriate. It is likely however that such fermentations will be of slow growing cells such as mammalian cells that do not require high rates of oxygen transfer. While the studies discussed in this paper may be of relevance in this field it is not the primary focus. Secondly, as deep space exploration becomes more developed it becomes necessary to recycle the carbon used in food systems, the so-called Controlled Ecological Life Support Systems (CELSS), and in waste processing subsystems. Here high rates of oxygen transfer are necessary to permit systems of reasonable weight, volumetric and power effectiveness.

PROBLEMS

a. Bubble rise velocities

In a conventional fermenter bubbles of air are introduced into the bottom of a vessel. The bubbles rise through the liquid transferring their oxygen to the liquid. In microgravity the bubbles simply will not rise. A conventional fermenter will therefore not work.

b. Oxygen transfer intensity

Figure 1 is an attempt to show the interaction between the exponential cell growth of yeast (the likely target organism) in the absence of oxygen limitation for a range of doubling times from 1 to 4 hours. This is indicated by the solid lines. At low cell densities, yeast can double in well under an hour. The broken lines show the cell mass that can be supported, at 50% carbon conversion, for differing oxygen transfer intensities of between 1 and 5 Kg $O_2/m^3/hr$. It shows that for cell dry masses of likely importance in a CELSS

environment that oxygen limitation will dominate under most conditions and should thus be the focus of our studies.

c. Blowing bubbles

The simplest heuristic example is blowing a bubble of air, density ρ_G, in a stationary fluid of density ρ_L. The bubble is being blown from a tube of diameter d_o into water of surface tension to produce a bubble which will eventually breakaway from the tube when a critical diameter d_b is reached. At that point it is possible to write a force balance on the bubble - the surface tension force will exactly balance the gravitational forces induced by density differences (and thus buoyancy).

$$\frac{\pi}{6} d_b^3 (\rho_L - \rho_G) g = \gamma \pi d_o$$

Rearranging gives the simple formula :-

$$d_b = \left(\frac{6 \gamma do}{g(\rho L - \rho G)} \right)^{1/3}$$

The implication of this equation is interesting when one examines the effect on d_b as g is reduced. Being on the bottom line of the equation it isseen that as $g \rightarrow 0$ $d_b \rightarrow \infty$. The physical interpretation of this is that the bubble diameter becomes infinitely large as the gravity becomes infinitely small or, more realistically, that a phase inversion will occur whereby one obtains a dispersed phase of liquid droplets in a continuous phase of gas. The usual situation is a continuous phase of liquid and a dispersed phase of gas.

d. Rigid spheres vs. internal circulation by convection

Assuming that the above problem can be overcome in some ingenious way, we are still left with another problem relating to bubble size. The rate of oxygen transfer from a bubble is given by:-

$$-d [O_2]/dt = K_l a (C_i - C_o)$$

where C_o , C_i are the bulk and interfacial concentrations of oxygen respectively, and a is the surface area of bubbles per unit volume of reactor. K_l has been extensively measured for a number of gases in water, particularly for large bubbles. In large bubbles internal circulation of the gas takes place, driven by density induced convection. This greatly enhances the rate at which mass transfer of oxygen takes place. Very small bubbles however readily attract impurities which adsorb on the surface of the bubble making in behave like a solid sphere and, more importantly for our purposes, the closeness of the bubble walls to each other inhibits the process of internal circulation and so reduces mass transfer many times. This produces the

paradoxical effect that mass transfer from large bubbles is frequently greater than from small bubbles, i.e., K_l goes through a maximum with respect to bubble diameter with mass transfer actually decreasing as the bubble diameter increases. Figure 2 below, based on the original graph of Motarjemi and Jameson(1978), shows this effect clearly. The effect is analogous to the situation encountered with multiple glazing of windows. If the separation between the panes of glass is too great then density gradients induce internal circulationwhich actually enhance heat transfer and so destroy the purpose of installing the insulation. For bubbles in microgravity no circulation will take place as the convective forces due to density and hence gravity will not be operable.

Small bubbles	Large bubbles
Large surface area.	Smaller surface area
Reduced internal circulation	Enhanced internal circulation.

In microgravity all bubbles will have no internal circulation and hence will have a poor mass transfer rate for the transport of oxygen.

SOLUTIONS

As in most technical situations one can deal with a problem by removing the conditions that cause the problem, learn to live with it, create a different environment in which the problem can be solved or avoid the need to solve the problem. Where the last solution is available it is usually to be preferred.

Solutions range from creating gravity artificially by rotating the equipment at a sufficient speed to induce the necessary gravity to rotating devices that contact the gases and liquids at high shear and ignore the microgravity. The solution proposed here is to avoid the need to solve the problem by separating out the gas phase that causes the problems. This can be done simply by filling the fermenter with tubing, silicone or fluorocarbon, which have a high permeability to oxygen. Calculations (Seshan et al, 1986) indicate that 10% of the fermenter volume occupied by silicone tubing should be more than adequate for the high oxygen rates envisioned in this fermentation. About 1% of the tubing would be capable of removing the carbon dioxide so produced. On the inside of the tube passes either air or oxygen gas separated from the liquid phase by the membrane. Another possibility is the use of oxygen carriers and carbon dioxide absorbers. A number of liquids have a high solubility for oxygen, among them obviously are the liquid silicones and fluorocarbons from which the membranes are made. Other possibilities include the synthetic hemoglobin analogs that are currently being developed. Carbon dioxide removers are available that range from the poorly reversible traditional absorbers such as monoethanolamine to the newly developed redox-switched substituted quinones and metallocenes (Bell et al, 1988) inwhich CO_2 is absorbed at one redox potential but rapidly given up by small changes in the potential. Calculations show that 1 kg $O_2/m_3/hr$ should be realistically obtainable. One of the hidden advantages of such a system is that while it is designed to operate in space it should operate equally effectively on the ground where most of the experimentation and

validation can be performed. Such systems have already been tested on a bench scale (Petersen G.R., P.K. Seshan, E.H. Dunlop. 1989. Phase separated membrane bioreactor:results from model system studies. Advances in Space Research, 1989. In Press.).

CONCLUSIONS

1. A conventional fermenter will not operate in microgravity.

2. A phase separated fermenter appropriately designed will support high cell densities at a high rate of growth.

3. Testing of the phase separated fermenter on the ground should provide most of the necessary design information without the need for expensive flight tests.

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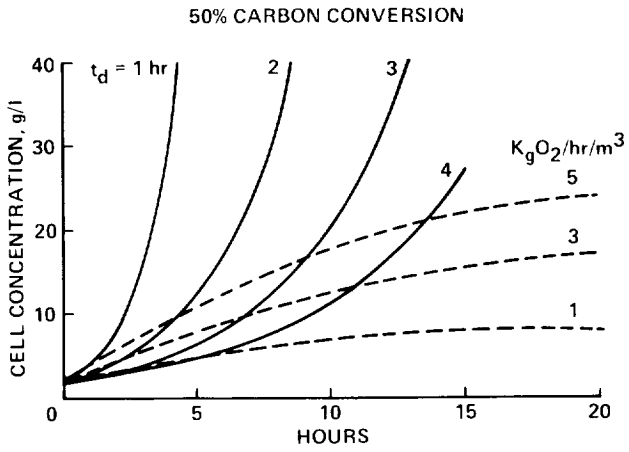

Figure 1.

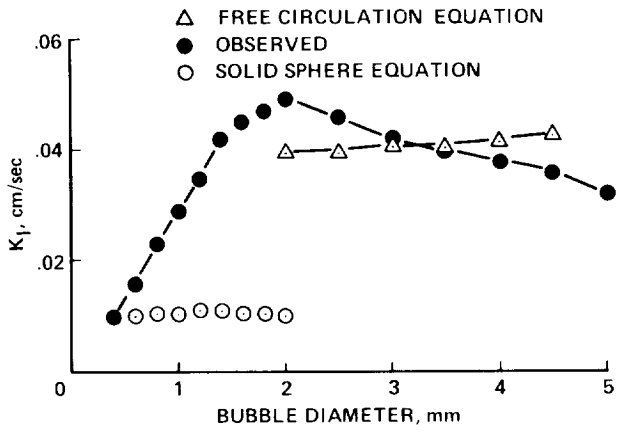

Figure 2.