Use of Film-Flow Reactors for Studying Microbiological Kinetics

WALTER J. MAIER

Department of Civil Engineering and Hydraulics, Institute of Technology, University of Minnesota, Minneapolis, Minnesota 55455

Received for publication 5 February 1968

The use of a film-flow reactor for studying the kinetics of substrate removal is described. The reactor provides a means of maintaining a uniform layer of biologically active slime which is stationary while the feed solution is made to flow over the slime surface in a thin film. The study was designed to evaluate process limitations in the trickling filter process which is designed for the biological removal of waste matter from dilute solutions (W. J. Maier, V. C. Behn, and C. D. Gates, J. San. Eng. Div., Am. Soc. Civil Eng. 93:91, 1967). The following discussion illustrates the use of a film-flow reactor and points out the advantages and disadvantages of such a model reactor.

From a theoretical viewpoint, the film-flow reactor has three advantages. (i) It holds the biologically active mass stationary and thus permits the making of rapid changes in environmental conditions such as composition of the growth medium and concentration of substrate. (ii) It allows for instantaneous control of the flow of nutrients. (iii) It allows regulating contact time between the bacterial mass and the medium, independent of flow rates.

The disadvantages stem from the relatively low rates of mass transfer which limit removal of nutrients at low concentrations of nutrient.

Apparatus. An inclined flat surface, made of 1-inch (2.54 cm) thick clear plastic, was used as a support for slime growth (Fig. 1); the surface is 11 cm wide and 60.5 cm long. Plastic has the advantage that it can be machined precisely and is inert and nontoxic. The plastic plate is bolted to a metal framework to prevent warping. Liquid medium is introduced into a calming basin whence it passes over a precisely machined overflow weir. The weir acts as a distributor to provide uniform film flow across the whole surface. The horizontal surface of the plate is covered with fiber-glass screen (spot-glued to the surface); the screen serves as a structural framework for slime growth; it is made of wire (0.028 cm diameter) woven 5 by 7 strands per cm; void space accounts for 80% of the volume defined by the edge-view volume of the screen.

Procedures and results. Slime growth is initiated by injecting inoculum into the flow of growth medium for a short period of time. After seeding, a small but continuous flow of medium is maintained and growth is allowed to fill up the void spaces in the wire mesh; this takes from 1 to 2 weeks. After the slime has filled the voids, excess growth is removed periodically by scraping with a knife edge. The thickness of the slime layer is thus controlled to the approximate thickness of the screen framework. Various thicknesses of slime can be achieved by superimposing successive layers of screen or by using screens of different thickness. The growth medium for the initial study consisted of a buffered salt solution with glucose as the sole source of carbon. Glucose was measured at the inlet and outlet to give a measure of rate of removal on the whole plate.

It has been shown from considerations of Reynolds number that the flow on a flat, inclined plane is in the laminar flow regime. Laminar flow can also be demonstrated by the use of dye injections which show that the flow lines are parallel to the surface of the slime layer. It follows that mass transport of nutrients from the liquid film to the slime layer is by molecular diffusion, which is relatively slow. However, the flat plate reactor has the advantage that the rate of mass transfer by molecular diffusion can be described mathematically, so that it becomes possible to distinguish between the situation where mass transfer is the rate-limiting factor and the situation where biological uptake is the rate-limiting factor. A general mathematical model which describes mass transfer and reaction at the solid surface of the inclined plane is described in the chemical engineering literature (R. B. Bird, W. E. Stewart, and E. N. Lightfoot, Transport Phenomena, John Wiley & Sons, Inc., New York, 1962, p. 495).

The film-flow reactor was used over a period of several months to define the effects of thickness of the slime layer, concentration of substrate, and medium composition.

The slime layer embedded in the screen was
maintained at a uniform and constant thickness by scraping periodically with a knife edge to remove new growth. This procedure had no measurable effect on the rate of removal of glucose. [Milligrams of glucose removed per 10 min: after overnight growth (and 15 min after scraping), 11.9; 0.5 hr after scraping, 11.9; 0.3 hr after repeat scraping, 11.4.] The scraping procedure was used every 3 to 5 hr during process-variable studies and gave reproducible results. This apparent insensitivity of the rate of biological uptake to removal of excess slime growth gave some preliminary indication that slime-layer thickness is not a critical variable.

The effect of slime-layer thickness on the rate of removal of glucose was tested by superimposing up to four layers of screen. The slime layer was built up by adding one screen at a time and allowing several days of growth to fill the void spaces of each layer. (With one screen, with a slime layer thickness of 0.05 cm, 11.2 mg of glucose was removed per 10 min; with four screens, with a slime layer thickness of 0.14 cm, 10.8 mg of glucose was removed per 10 min. Fresh medium contained 100 mg of glucose per liter.)

The rate of removal of glucose was found to be independent of the thickness of the slime layer. These observations suggest that the surface of the slime layer is the major site of metabolic activity, and increasing the thickness of the slime beyond 0.05 cm offers little advantage for glucose utilization when using media containing relatively low concentrations of substrate.

To provide some perspective on the effectiveness of the slime layer, the rate of removal of glucose was compared with results from a well-mixed reaction vessel using the same medium and the same source of inoculum. This comparison indicates that a depth of one to two cells can account for the observed rate of glucose removal. In effect, the film-flow reactor provides a very active surface which behaves like a catalytic surface in a chemical reaction system.

The evaluation of a series of feed solutions containing different concentrations of glucose substrate provides a good example of the versatility of the film-flow reactor model. Such tests can be carried out in less than 0.5 hr per feed solution. Typical results are plotted in Fig. 2, showing rate of removal of glucose for media containing from 25 to 980 mg/liter; rate of removal increases with glucose concentration but levels out and becomes essentially independent of substrate concentration at high concentrations of glucose. The slower uptake at low concentrations can be explained in terms of mass transfer limitation, whereas it cannot be explained in terms of a reduced growth rate at lower concentrations of substrate, as shown by work of several investigators (W. J. Maier, V. C. Behn, and C. D. Gates, J. San. Eng. Div., Am. Soc. Civ. Eng. 93:91, 1967; E. Stumm-Zollinger, Appl. Microbiol. 14:654, 1966; J. S. Jeris and R. R. Cardenas, Jr., Appl. Microbiol. 14:857, 1966). The maximal possible rate of mass transport of glucose from the liquid film to the slime surface, as calculated from the previously mentioned mathematical model, is shown in Fig. 2 for comparison. It is obvious that the observed removal is limited by mass transfer with media containing low concentrations, e.g., below 100 mg/liter. However, when higher glucose concentrations are used, the potential maximal rate of mass transfer is substantially higher than the observed rate of removal, which suggests that biological...
uptake is rate-limiting at higher glucose concentrations.

There is no doubt that mass-transfer limitation at low concentrations of substrate is a disadvantage for process-variable studies. However, this disadvantage is overcome by the fact that potential mass-transfer limitations can be anticipated by using available information on molecular diffusion coefficients in conjunction with the previously mentioned mathematical description of the film-flow reactor. Furthermore, this is not a problem at higher substrate concentrations.

This study was carried out at Cornell University under a Public Health Service traineeship award. We thank V. C. Behn and C. D. Gates for their help and encouragement.