CONCENTRATION OF EGG WHITE BY ULTRAFILTRATION

R. Edward Payne and Charles G. Hill, Jr.
Department of Chemical Engineering
AND
Clyde H. Amundson
Department of Food Science
University of Wisconsin, Madison, Wisconsin 53706

(Received for publication December 5, 1972)

Abstract

Ultrafiltration was used to concentrate egg white by partially removing water and other low molecular weight species. Total solids concentrations as high as 41% (representing removal of 80% of the initial water) were obtained. Studies were made of the influences of feed flow rate, feed temperature, and pressure difference across the membrane on the performance of ultrafiltration membranes. Optimum conditions of operation correspond to a maximum feed temperature and feed flow rate consistent with product integrity and membrane life. No physical degradation of egg white proteins could be distinguished by electrophoretic studies. This mode of concentration represents an improvement over conventional methods of concentration which tend to degrade the whipping characteristics of egg white by thermal and/or physical denaturation of proteins. Average flux and cost per pound of water removed indicate that there is a potential commercial application for concentrating egg white by ultrafiltration.

The widespread use of egg white in the baking and candy industries arises from its ability to form stable foams which support relatively large quantities of sugar and/or flour *(5, 8)*. Present methods of concentrating egg white frequently diminish its desirable functional properties by shear damage, thermal denaturation of proteins, or induction of the Maillard reaction between glucose and amino acids *(2)*. However, several advantages may be gained by concentrating egg white, e.g. a reduction in the costs associated with packaging, freezing, transporting, and storing this material *(6)*.

Reverse osmosis and especially ultrafiltration techniques offer economic methods for concentrating egg proteins by removing water and other low molecular weight species. These approaches offer potential savings over more conventional methods of water removal which require greater expenditures of energy. The degree to which egg white may be concentrated by membrane techniques is limited by two factors: (*a*) the viscosity of the concentrate as it becomes too great to pump economically, and (*b*) the transmembrane flux when it is reduced to an impractical level.

Considerable interest in concentrating egg white by membrane processes has developed since Lowe reported that reverse osmosis can produce an egg white concentrate with excellent functional properties. Lowe demonstrated that it is possible to achieve concentrations of 30% total solids. The concentrate produced by Lowe was evaluated in baking tests. Specific volumes of meringue and angel cake heights were comparable to those of fresh egg white under equivalent conditions of NaCl concentration, pH, and whip time *(8)*.

Ultrafiltration differs from reverse osmosis in that the membrane is permeable to both water and low molecular weight substances rather than to water alone. Consequently the pressure requirements are substantially less.

One may argue that it will be necessary to use some method such as spray drying to remove the water remaining after membrane processing, and that thermal or physical damage of the protiens will occur. However, solids spray-dried from an egg white concentrate obtained by ultrafiltration were found to reconstitute more readily than the powder formed from liquid egg white via spray drying because the preconcentrated liquid forms a relatively high density product *(8)*. In addition to the lower cost for removing the water and other low molecular weight species, an approach using membrane separations would preserve or improve desirable functional properties of the concentrate *(2, 8, 10)*.

Ultrafiltration appears to be a more appropriate membrane separation technique than reverse osmosis for concentrating egg white. The ultrafiltrate contains glucose and inorganic salts as well as water so a partial fractionation is accomplished in addition to the concentration. Because these species would contribute to the osmotic pressure of the concentrate stream when using reverse osmosis and because the transmembrane flux is given by

$$J = \frac{\Delta P - \Delta \pi}{R_m + R_f + R_d}$$

where

J = trans-membrane flux
ΔP = trans-membrane hydrostatic pressure difference
$\Delta \pi$ = osmotic pressure difference across the membrane
R_m = flow resistance caused by the membrane
R_f = flow resistance caused by fouling of the membrane
R_d = flow resistance caused by the hydrostatic

boundary layer, the hydrostatic pressure required for ultrafiltration will be less than that required for reverse osmosis. Since high shear rates are one cause of physical damage to the proteins of egg white, the damage to the functional properties is reduced with the lower operating pressures of ultrafiltration *(1, 9)*. At lower pressures, pumping costs are reduced and the equipment costs are less since material strength requirements are not as great.

The present investigation was carried out to determine the technical and economic feasibility of concentrating egg white by ultrafiltration. The influence of such design parameters as temperature, pressure, and Reynolds number were examined.

Apparatus and Materials

Large tube membrane configurations were used in all experiments. Modules supplied by two manufacturers were employed in the present investigation. Some experiments utilized a pilot ultrafiltration unit containing type HFA-180 membranes obtained from Abcor, Inc. of Cambridge, Massachusetts, whereas others involved type 215 VDR ultrafiltration membranes in a Mark IV module obtained from Calgon Havens, Pittsburgh, Pennsylvania.

Abcor unit

The Abcor ultrafiltration modules consisted of a membrane cast seamlessly on the inside of a 54-inch long inert, porous, polyethylene 1-inch ID tube. The membrane and support tube are encased in a clear polystyrene permeate collection shroud. The shroud has ports on either end to permit collection of the permeate. The feed is introduced and withdrawn axially through 1-inch ID stainless steel connectors. The stainless connector is secured to the membrane unit by PVC fittings. The effective membrane area of each unit is 1.1 ft^2. The maximum operating pressure at ambient temperature is 50 psi. Membrane operating temperatures are restricted to between 40 and 140 F.

Calgon-Havens unit

The Calgon Havens module used utilizes several 0.5-inch ID tubes nested together. The membrane is cast seamlessly on the inside of a porous, epoxy-bounded, fiberglass support tube. Eighteen of these tubes are placed inside a Mark IV Osmotik module and connected in series by U-bends. Each tube is fitted with 0.25 inch polyethylene volume displacement rods (VDR) which act as detached turbulence promoters. Increased turbulence enhances bulk mixing and hence, the trans-membrane flux *(7)*.

Egg white

The egg white used in this study was obtained from Mazo Egg and Produce, Inc., Middleton, Wisconsin. This facility is a commercial egg breaking plant, USDA Inspected Egg Products Plant 765. The egg white was homogenized, pasteurized, and cooled but unfrozen.

Results and Discussion

The effects of temperature, Reynolds number, and feed composition on performance of two types of ultrafiltration modules were investigated. By varying each of these parameters independently, its influence on the trans-membrane flux of the ultrafiltration modules could be determined. Each data point represents at least two replications while operating at steady state.

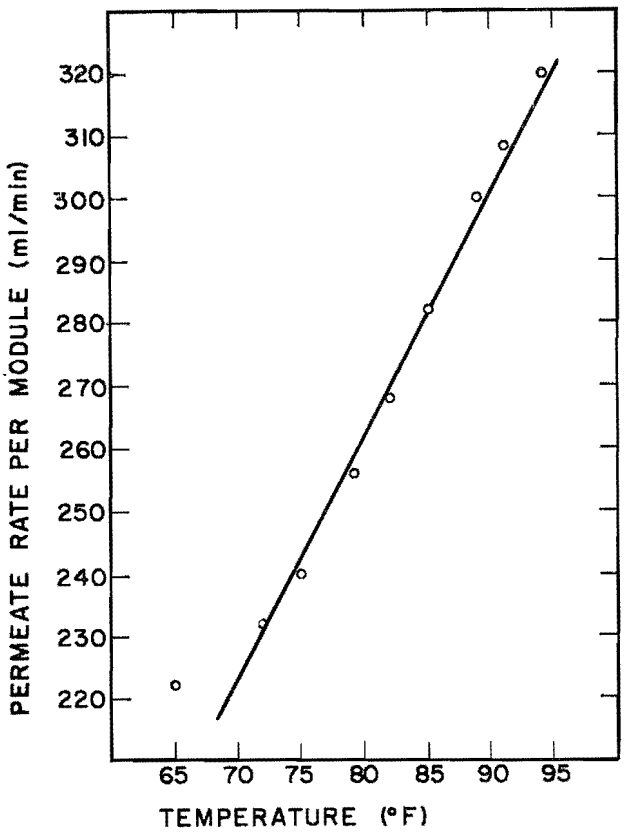

Figure 1. Temperature dependence of flux for egg white. Calgon Havens 215 VDR; feed flow rate: 1.5 gpm; and pressure: 175 psi.

Temperature dependence of flux for egg white (Calgon Havens)

The permeate rate for Calgon Havens ultrafiltration membranes exhibited a strong temperature dependence as shown in Fig. 1. By plotting the same data as a function of inverse absolute temperature, a linear Arrhenius type plot was obtained. From the slope of this plot, an activation energy of approximately 5 kcal/g mole is obtained. This value is the same as that obtained with the Abcor membranes and with those obtained by Wiley et al. *(11)* and by Fenton-May *(4)* using cellulose acetate membranes to ultrafilter waste liquors from a paper mill and cheese whey, respectively.

Influence of pressure upon flux for egg white (Calgon Havens)

By holding the temperature, flow rate or degree of turbulence, and the composition constant, the influence of the average module pressure was examined. The trans-membrane flux at steady state varied with pressure in the manner shown in Fig. 2.

The buildup of a protein gel adjacent to the mem-

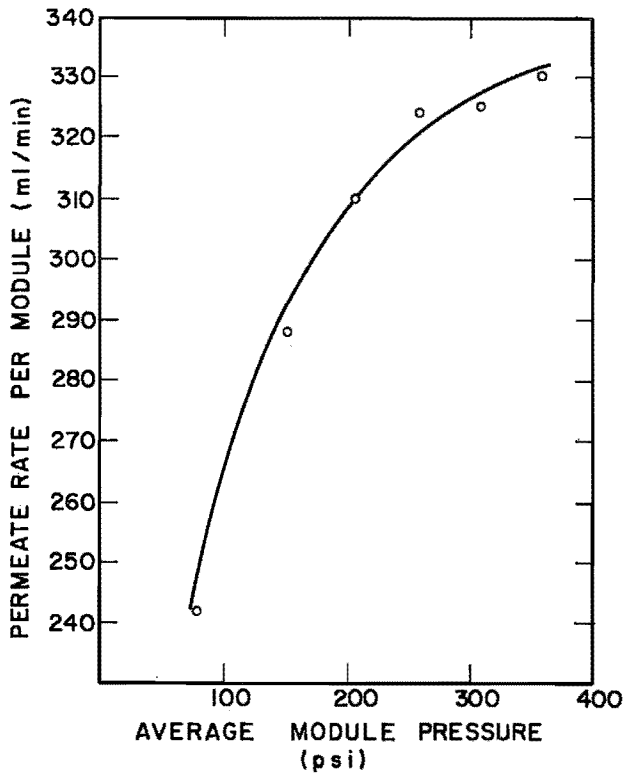

Figure 2. Pressure dependence of flux for egg white. Calgon Havens 215 VDR; feed flow rate: 1.5 gpm; and temperature: 29 C.

brane can impair the performance of the system. The phenomenon is a result of concentration polarization and is depicted in Fig. 3. As indicated in this figure, the proteins of egg white are carried with the solvent as it is transported toward the membrane surface. The macrosolute is rejected at the membrane surface resulting in an accumulation of protein molecules at the surface. At sufficiently high fluxes this accumulation may lead to formation of a protein gel or "cake" on the surface of the membrane. This gel layer acts as an added resistance in series with the flow resistance caused by the membrane itself and impedes the solvent flux.

As the average module pressure was increased, the protein gel layer or "cake" on the membrane surface thickened until the back diffusive transport equaled the convective transport of macrosolute to the membrane. In the right hand portion of Fig. 2, it can be seen that the flux is approaching an asymptotic value as a limit. As equation 1 indicates, the permeate flux should be directly proportional to the pressure difference across the membrane in the absence of concentration polarization and significant osmotic pressure effects. With egg white, however, the fouling resistance R_f is important because of the ease with which the protein molecules can form a gel layer. Consequently nonlinear behavior is observed at the flux rates studied in this investigation.

Reynolds number dependence of flux for egg white (Calgon Havens)

The recommended flow rate of concentrate should lie in the range of 1.2 to 1.5 gpm. The effect of Reynolds number or flow rate is given in Fig. 4 for constant operating conditions of temperature, press-

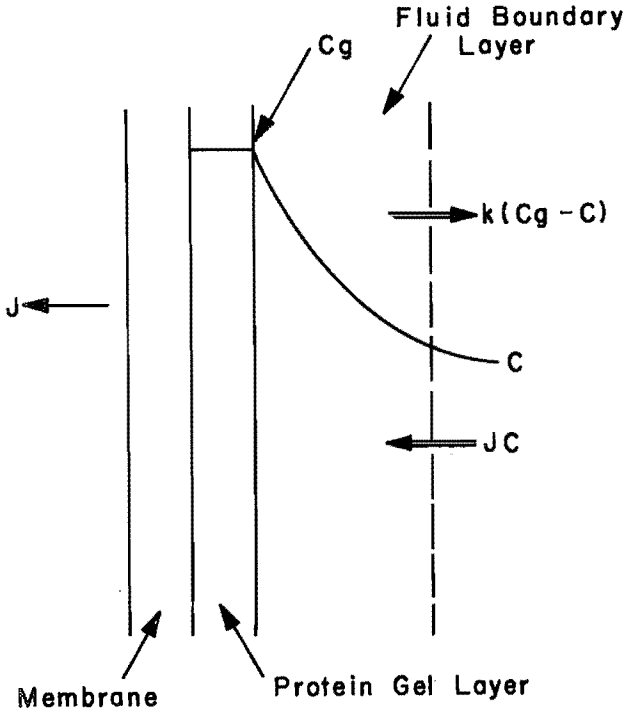

Figure 3. Steady state concentration polarization.

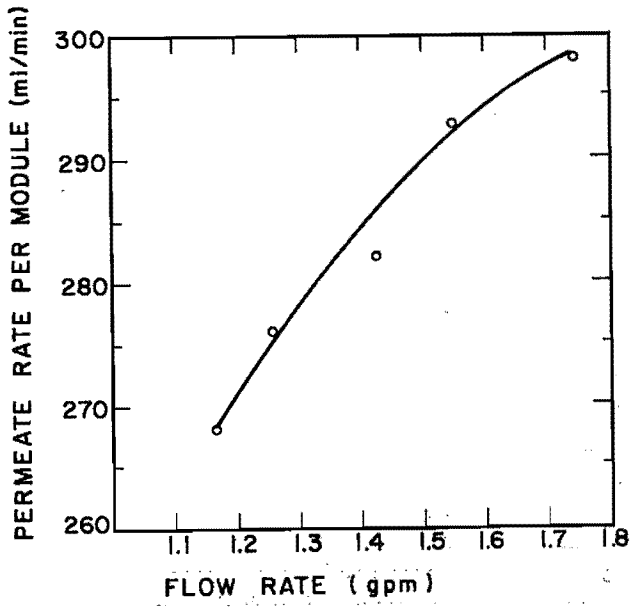

Figure 4. Flow rate dependence of flux for egg white. Calgon Havens 215 VDR; temperature: 29 C; and pressure: 190 psi.

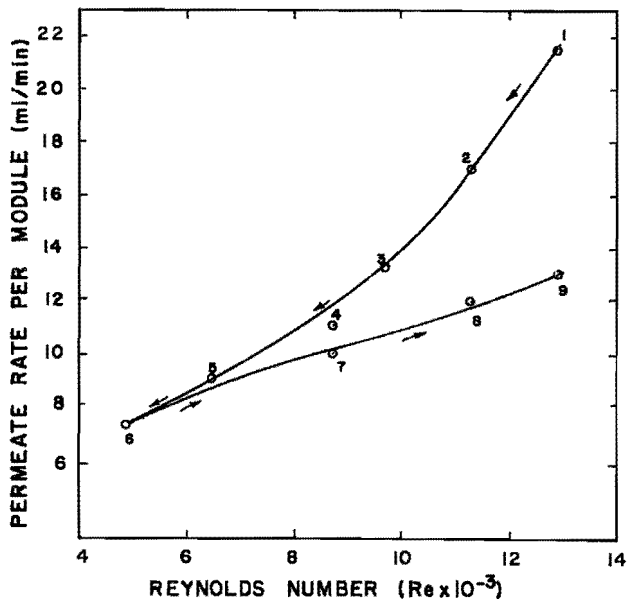

Figure 5. Hysteresis experiment with egg white. Abcor HFA-180; temperature: 87 F; pressure: 23 psi.

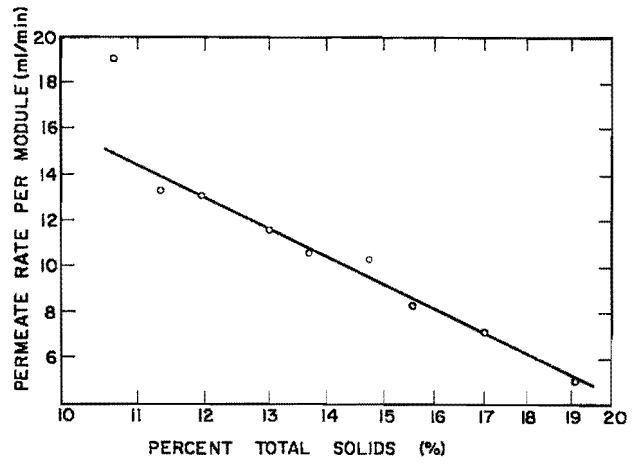

Figure 6. Flux rate dependence upon total solids for egg white. Abcor HFA-180; temperature: 91 F; feed flow rate: 15 gpm; pressure: 25 psi.

ure, and feed composition. The figure again demonstrates the influence of concentration polarization on the permeate rate. That is, as the Reynolds number was increased, the permeate rate was increased.

Using the Abcor system with the feed composition held constant, a hysteresis-type experiment was performed. That is, the feed flow rate was lowered from the maximum limit imposed by mechanical constraints of the system in prescribed increments to the minimum flow rate and then returned to the maximum flow rate. During the course of the experiment, the dependence of the permeate rate on the flow rate was recorded. These results are presented in Fig. 5. The permeate rate associated with the final maximum flow rate was substantially reduced from the initial flow rate. Therefore, the flow history of the membrane influenced its permeate rate. Similar experiments with skim milk in Calgon-Havens modules demonstrated that the permeate rate appeared to be a function of the lowest flow rate to which the membrane was subjected *(4)*. These experiments tend to indicate that the gel layer thickens with reduced Reynolds number thus reducing the trans-membrane flux. Moreover, the influence of the gel layer was not entirely reduced by increasing the Reynolds number indicating that this layer has a permanent influence once it has been established.

Influence of increasing feed concentration upon flux (Abcor)

By returning only the concentrate to the feed tank and disposing of the permeate, the effect of concentrating the feed was studied. In Fig. 6 the permeate rate for egg white is plotted against percent total solids in a semilog plot.

As the feed became more concentrated, the flux decreased exponentially. This result may be predicted theoretically from classical chemical engineering mass transfer equations. That is, a steady state flux value is established when the convective transport of solute towards the membrane is reduced to the same value as the back diffusion of the solute away from the gel layer.

Egg white was concentrated to 41% total solids with the Calgon-Havens module with no apparent product damage. However, the permeate rate was reduced by an order of magnitude from the initial value. Furthermore, the amount of protein which passed through the membrane was negligible regardless of the total solids concentration.

By increasing the total solids content of the egg white, the effect of concentration polarization or a gel layer upon the solvent flux becomes more pronounced. The influence of the protein "cake" upon the transport of microsolutes was also investigated. The concentration of glucose in the concentrate and permeate was determined by Glucostat enzymatic assay. During the course of concentrating egg white, there appeared to be no interference in the transport of glucose by the protein gel layer.

Estimation of shear damage to the proteins of egg white

Electrophoresis was utilized to estimate the damage to the proteins of egg white by the shear forces experienced during extended periods of operation. A comparison between egg white as it was delivered and that which had been concentrated for more than 8 hr shows no new bands and no band disappearing.

Therefore, it was concluded that the albumen suffered no appreciable damage by shear stress. Approximately 100 μg of proteins were placed on the

gel and < 1 μg could have been detected. Therefore, shear damage of less than 1% of the total protein would be distinguishable.

ECONOMIC FEASIBILITY STUDY

After completing the technical feasibility study, the economic implications of this research were investigated in part. The basis for this analysis was a 250,000 lb. per day facility. Table 1 compares the costs associated with ultrafiltration, spray drying, and freeze drying. In each instance, egg white was concentrated to 25% total solids.

TABLE 1. COMPARISON OF ULTRAFILTRATION, SPRAY DRYING AND FREEZE DRYING COSTS (INCLUDING LABOR)

Unit operation	Cost (cents/lb. water removed)
Ultrafiltration	0.206
Spray drying	0.950
Freeze drying	7 - 15

Consequently, it appears to be economically attractive to use ultrafiltration to obtain a product containing 25% total solids from liquid egg white (12% total solids) and then to spray dry or freeze dry to approximately 3% moisture. Studies have indicated that the product obtained in this fashion reconstitutes more readily than the egg white powder obtained by spray drying alone.

Moreover, if the concentrate containing 25% total solids were to be freeze dried, the ultrafiltration concentration step would be still more attractive as can be seen in Table 1.

CONCLUSIONS

For ultrafiltration membranes in general, the solute rejection characteristics are invariant with temperature. However, the strong dependence of the transmembrane flux on temperature as shown in Fig. 1 suggests that egg white should be concentrated at the highest possible temperature consistent with membrane life and sanitary conditions.

Pressure dependence of the flux is given by Fig. 2. As the upper limit of the operating pressure range was approached, the flux became less dependent on the applied pressure and was limited by the rate of back diffusion of solute.

The importance of good bulk mixing is demonstrated by Fig. 4. To minimize the effects of concentration polarization and to maximize the flux rate, the system should be operated at high feed flow rates. An economic compromise between higher feed velocities and added membrane area should be made for a given concentration.

In summary, the permeate rate was increased by operating at high feed velocities and high temperatures subject to considerations of product and membrane safety and the economics of operation.

ACKNOWLEDGMENTS

The authors wish to acknowledge the financial support of the State of Wisconsin through the University-Industry Research Program and the Research Committee of the University of Wisconsin. We also thank Abcor, Inc. and Calgon Havens for their cooperation.

REFERENCES

1. Berquist, D. H., and C. G. Stewart. 1952. Atomization as a factor affecting quality in spray dried albumen. Food Technol. 6:201.
2. Brown, S. L., and M. E. Aabik. 1967. Effect of heat treatments on the physical and functional properties of liquid and spray dried egg albumin. Food Technol. 21:87.
3. Fenton-May, R. I., C. G. Hill, Jr., C. H. Amundson, and P. D. Auclair. 1972. Recent advances in separation techniques. AIChE Symposium Series 68:31.
4. Fenton-May, R. I. 1971. Ph.D. thesis, Dept. of Chem. Engr., Univ. of Wisconsin.
5. Forsyth, R. H. 1960. Eggs, p. 188-220. In S. A. Matz (ed) Baking technology and engineering. Avi Publishing Co., Westport, Conn.
6. Gordon, A. 1971. Egg products - 1, Food Proc. Ind. 40:27-30.
7. Lowe, E., and E. L. Durkee. 1971. Dynamic turbulence promotion in reverse osmosis processing of liquid foods. J. Food Sci. 36:31-32.
8. Lowe, E., E. L. Durkee, R. L. Merson, K. Ijichi, and S. L. Cimino. 1969. Egg white/concentrated by reverse osmosis. Food Technol. 23:753-762.
9. MacDonnell, L. R., H. L. Hanson, R. B. Silvox, H. Lineweaver, and R. E. Feeney. 1950. Shear-not pressure harms egg white. Food Ind. 22:273-276.
10. Porter, M. C., and A. S. Michaels. 1971. Membrane ultrafiltration. Chem. Technol. 248-254.
11. Wiley, A. S., et al. 1972. Reverse osmosis concentration of dilute pulp and paper effluent. GOP 12040 EEL 02/72 Water Pollution Control Series.