Separation Science and Technology
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713708471

The Vibrating Ultrafiltration Module. Performance in the 50-1000 Hz Frequency Range

F. Vigo[a]; C. Uliana[a]; E. Ravina[b]; A. Lucifredi[b]; M. Gandoglia[b]
[a] INSTITUTE OF INDUSTRIAL CHEMISTRY UNIVERSITY OF GENOA, GENOA, ITALY [b] INSTITUTE OF MECHANICS OF MACHINERY UNIVERSITY OF GENOA, GENOA, ITALY

To cite this Article Vigo, F. , Uliana, C. , Ravina, E. , Lucifredi, A. and Gandoglia, M.(1993) 'The Vibrating Ultrafiltration Module. Performance in the 50-1000 Hz Frequency Range', Separation Science and Technology, 28: 4, 1063 — 1076
To link to this Article: DOI: 10.1080/01496399308029238
URL: http://dx.doi.org/10.1080/01496399308029238

SEPARATION SCIENCE AND TECHNOLOGY, 28(4), pp. 1063–1076, 1993

The Vibrating Ultrafiltration Module. Performance in the 50–1000 Hz Frequency Range

F. VIGO and C. ULIANA
INSTITUTE OF INDUSTRIAL CHEMISTRY
UNIVERSITY OF GENOA
16132 GENOA, ITALY

E. RAVINA, A. LUCIFREDI, and M. GANDOGLIA
INSTITUTE OF MECHANICS OF MACHINERY
UNIVERSITY OF GENOA
16145 GENOA, ITALY

Abstract

The effect of mechanical vibrations on the ultrafiltration of oily emulsions was studied in the 50–1000 Hz range. A cylindrical vibrating module was assembled and coupled with an electrodynamic exciter, controlled by a computerized system. The ultrafiltration experiments were run with a 20% cutting oil/water emulsion at different working conditions. The experimental data demonstrated that both vibration amplitude and frequency are effective in enhancing membrane performance. The influence of the frequency is more marked. Energy consumption was evaluated, and simple equations were proposed in order to predict both performances and energy requirements.

INTRODUCTION

As is well known (*1*), ultrafiltration (UF), thanks to particular kinds of membranes, enables separation of high molecular weight compounds or molecular aggregates from a solvent or dispersing medium (usually water) without involving a phase change. The main parameters controlling such a process are pressure, temperature, and concentration of the compound to be separated.

The higher the concentration, the lower the flux of permeate due to a "polarization" phenomenon arising at the membrane surface.

Most industrial UF plants keep the surface concentration low by recycling the feed at speeds ranging between 2 and 5 m/s. Unfortunately, this implies high energy consumption, and so people working in this field have tested new techniques suitable for obtaining better efficiency (*2*). Among these attempts have been turbulence promoters (*3*), Couette motion (*4–6*), pulsations (*7*, *8*), and vibrations (*9*).

It has been reported (*10*) that heat transfer is enhanced by acoustical vibrations, and investigators have applied vibrations to both water and air (*11*, *12*). Iraqi scientists (*13*) recently reported the influence of vertical vibrations on free convection heat transfer from a horizontal cylinder in air and studied the effect on the Nusselt number. In the field of ultrafiltration, some work has been done by Russian workers (*9*).

In a previous paper (*14*) it was shown that vibrations can influence the performance of ultrafiltration. Mechanical vibrations of frequencies ranging between 0 and 50 Hz were applied to a cylindrical membrane during the ultrafiltration of oily emulsions. The results were promising and showed that membrane performances increased with frequency. Nevertheless, some drawbacks were met due to the difficulty of obtaining high frequencies by mechanical devices because of the large energy losses involved.

This led us to consider using electromagnetic devices able to produce higher frequency vibrations and working at better efficiency conditions. The experiment was developed in cooperation with the Mechanics of Machinery Institute of Genoa University. This paper describes the results obtained.

EXPERIMENTAL

Ultrafiltration Module

A cylindrical permeator was used, as depicted in Fig. 1. It consisted of a drum carrying a Celgard 3500 (Celanese) membrane housed in a cylindrical shell. The membrane area was 0.0065 m^2.

A permeator was connected to a UF circuit equipped with pressure and temperature controls (Fig. 2A). Sinusoidal vibrations were produced by means of an electrodynamic exciter body (Bruel & Kjiaer type 4805) equipped with a general purpose head (type 4812), controlled by a feedback system (B & K conditioning amplifier type 2626, exciter control type 1047, power amplifier type 2707). An accelerometer (B & K type 4393) connected to the end of the membrane shaft was used both to obtain information about the dynamic behavior and to control the feedback system. The force applied to the membrane support was measured by a load cell (force transducer, B & K type 8200). The mechanical parameters (acceleration and force) were sent to a Hewlett-Packard Paragon data acquisition system connected to a HP 9000/300 workstation for signal processing and monitoring.

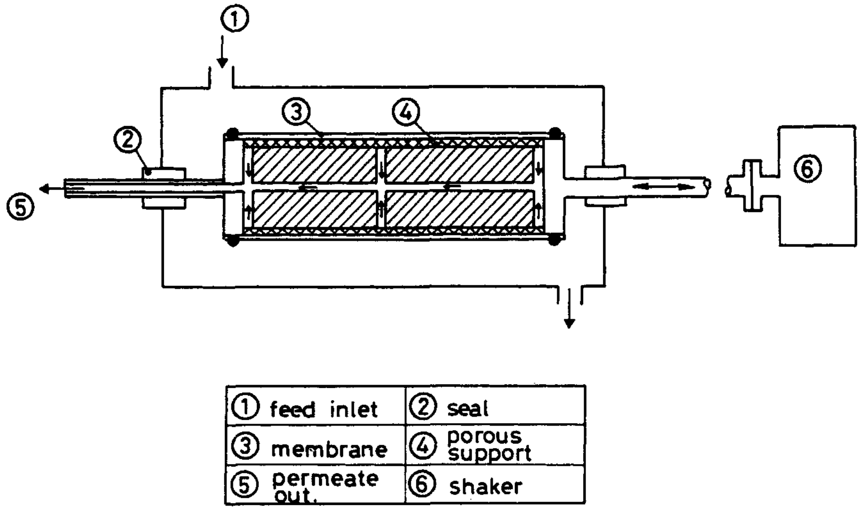

FIG. 1. Schematic of the permeator.

A schematic representation of the basic instrumentation setup is shown in Fig. 2B. The membrane shaft and the head of the shaker were connected by a steel rod. Two different configurations of the rod and the membrane shaft were considered: (a) rod and shaft aligned or (b) rod and shaft orthogonal. Because of the cylindrical geometry of the membrane, the second configuration was adopted.

During the tests, a second accelerometer (not shown in Fig. 2B) was placed on the exciter head in order to compare the input signal to the membrane with the one received by the shaft. These two signals could be different due to the stiffness characteristics of the rod.

The permeate flux was measured by weighting the liquid drawn off the central axis of the drum. The separation factor was obtained by measuring the residual oil in the permeate by infrared spectroscopy.

All the experiments were run with a 20% cutting oil emulsion at 313 K.

RESULTS AND DISCUSSION

Influence of the Vibration Amplitude and Frequency

Oily emulsions ultrafiltration was performed by means of the above described system while controlling and monitoring the operative parameters. The permeate flux and separation power (rejection) were measured

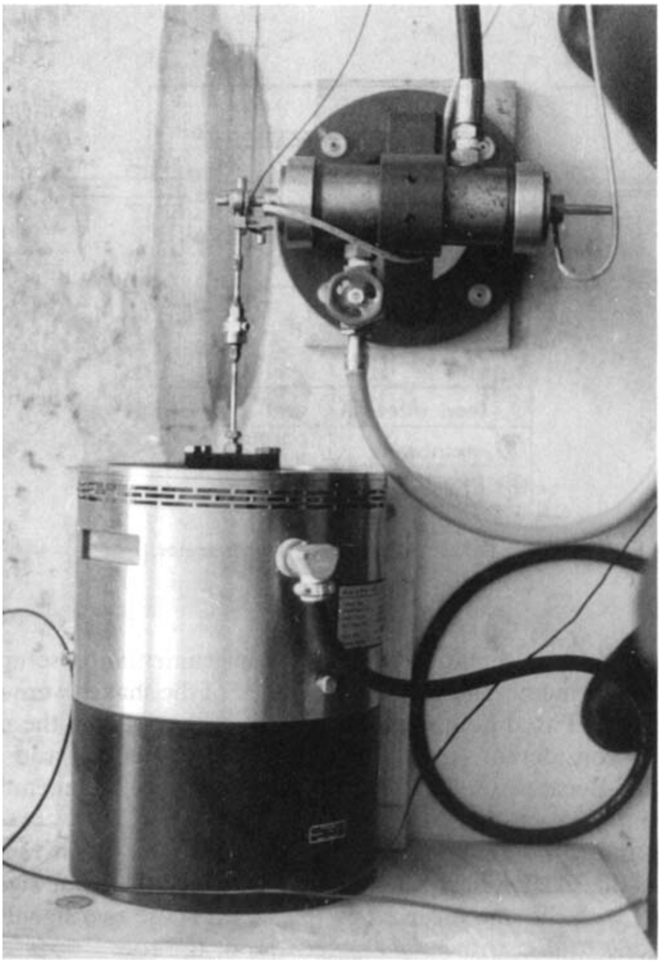

FIG. 2A. Coupling of the module with the exciter.

15 minutes after each change of working conditions in order to reach steady-state conditions at the membrane surface.

The experimental UF performances for permeate flux F ($L \cdot m^{-2} \cdot h^{-1}$) and oil rejection R (%) are reported in Figs. 3–6 as functions of the vibration frequency H (Hz) and vibration amplitude δ (m), along with trends predicted by some simple relationships reported later in this article.

The excitation frequency plays a fundamental role in UF performance, affecting both permeate flux and rejection. The data obtained can be com-

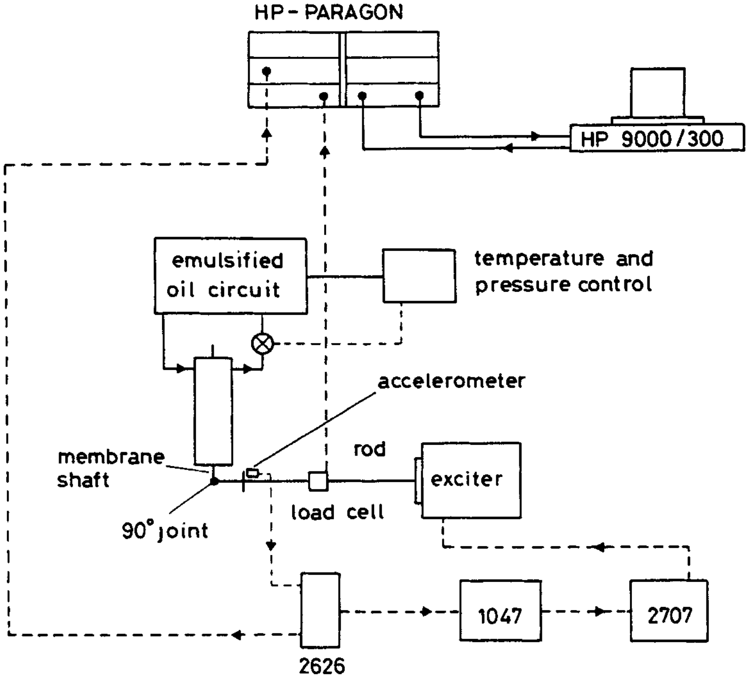

FIG. 2B. Experimental apparatus.

pared with those of previous work (*14*) to only a certain extent because of the different kinds of oil emulsions employed. Moreover, a permeate flux value different than zero was measured at vibration amplitude = 0. This is due to squeezing of the unseparated emulsion through the membrane by pressure ("parasitic" permeation).

The influence of frequency is evident in Fig. 5, which was obtained by elaboration of Fig. 3.

The behaviors of the permeate flux in Figs. 3 and 5 and the rejection in Fig. 4 are similar to those observed during previous experiments involving rotating (*5*) and low-frequency vibrating modules (*14*). This result could be foreseen because the product $2H\delta$ represents the mean shift speed of the membrane surface and, as has been demonstrated, surface speed affects membrane performance (*5*). The permeate fluxes and the rejection measured in this experiment are much higher than those expected in a rotating module running at the same surface speed.

This fact is illustrated by Fig. 6 where the permeate flux F is plotted against the $2H\delta$ value. It can be observed that permeate fluxes are not

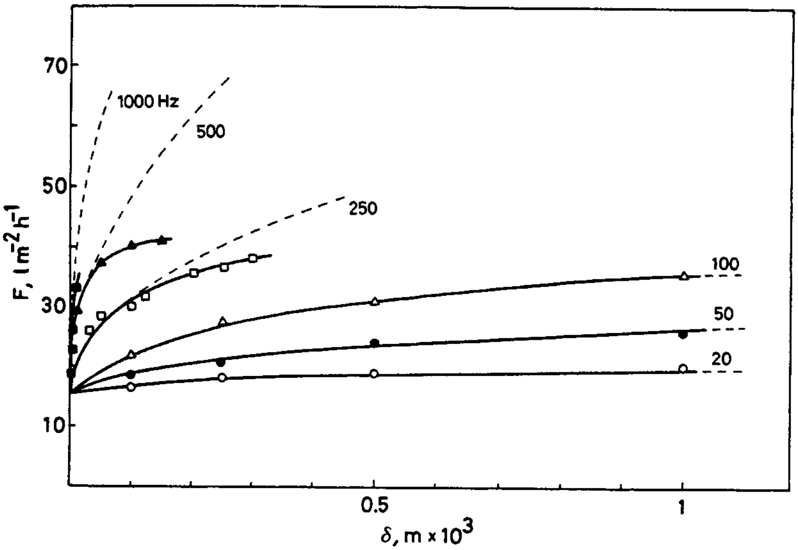

FIG. 3. Permeate flux (F) measured at different vibration frequencies (H) as a function of the amplitude (δ). UF tests run at 800 kPa pressure. Full lines: Experimental values. Dashed lines: Calculated trend.

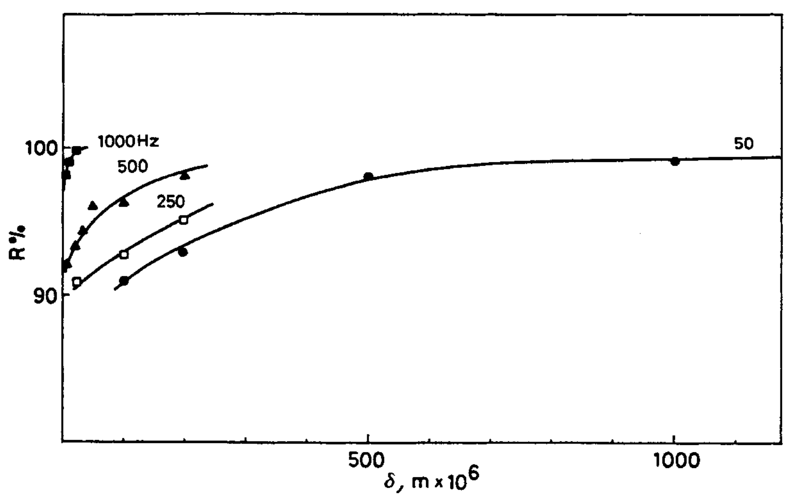

FIG. 4. Influence of the vibration frequency (H) and amplitude (δ) on the oil rejection (R, %).

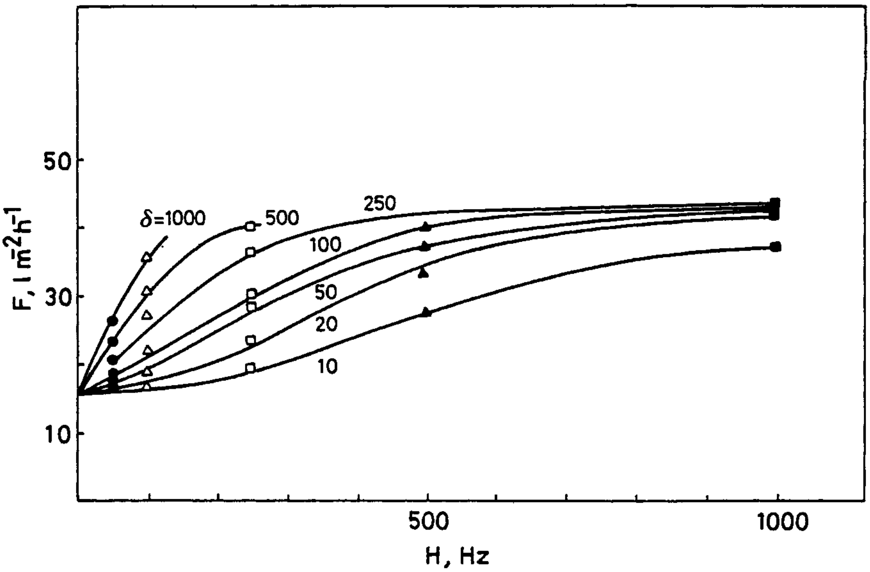

FIG. 5. Influence of the vibration frequency (H) on permeate flux (F) measured at different amplitudes (δ). Experimental conditions as in Fig. 3.

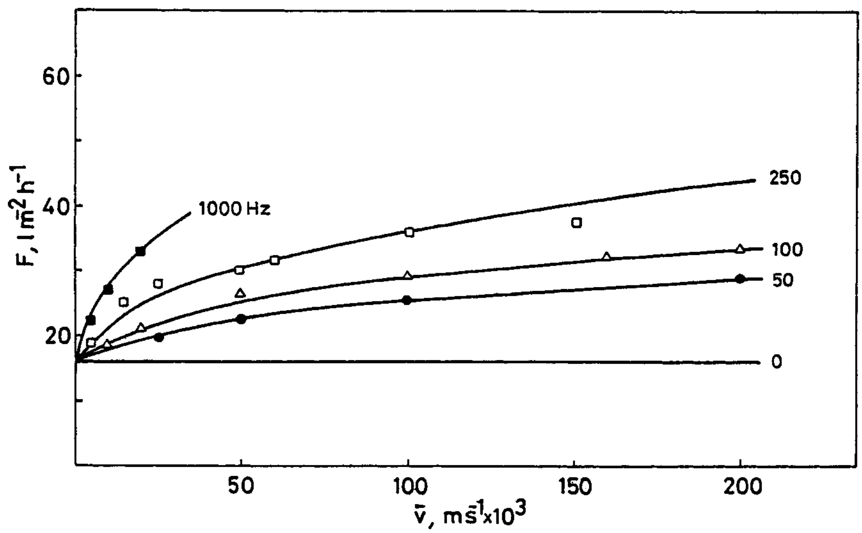

FIG. 6. Influence of the mean surface speed ($2H\delta$) on membrane performance (permeate flux F). Experimental conditions as in Fig. 3.

strictly proportional to the membrane surface speed as they were in the case of rotating modules. The effect of frequency is quite marked: higher fluxes are measured at 1000 Hz than at 100 Hz while keeping the mean speed constant. This difference increases with increasing overall speed due to the lower contribution of the "parasitic" permeation. In the case of a rotating module, the permeate flux and rejection at similar speed conditions were close to zero.

The product $2H\delta$ is a quantity proportional to the so-called vibrational Reynolds number as reported by Raben (*10*):

$$\mathrm{Re}_v = d_e \bar{v} \rho \mu \quad (1)$$

where d_e = equivalent diameter of an annular vessel
$\bar{v}$ = mean vibrational speed (= $2H\delta$)
ρ = fluid density
μ = fluid viscosity

The effect of a change in the vibrational Reynolds number cannot be rigorously applied in our case because a mean diameter for d_e cannot be defined.

With reference to the above reported relation, the mass transfer, which corresponds to the permeate flux F, should be independent of frequency if the average vibration speed is constant. Our experimental results demonstrate that F is still dependent on the frequency. For example, a 0.0001 m/s speed is sufficient to obtain 18 $L \cdot m^{-2} \cdot h^{-1}$ flux at 50 Hz, and 40 $L \cdot m^{-2} \cdot h^{-1}$ at 500 Hz.

This fact can be explained by taking into account that the boundary layer close to the membrane surface is affected not only by the mechanical effect of the vibration ("sieve" effect) but also by a chemicophysical energy transfer. This transfer is similar to a heating effect due to ultrasounds, and it depends more on frequency than on the vibration amplitude. This phenomenon seems to be related to the application of ultrasonic vibrations, and it becomes evident only if vibrations are applied to the membrane. In the case of application to the whole fluid, the energy is "diluted" and the effect is much lower.

Influence of the Pressure

The module used during our experiment was small in comparison with those used in our previous work (*14*). The dimensions were suggested by the need to limit the mass to be displaced and, consequently, the power of the vibration exciter.

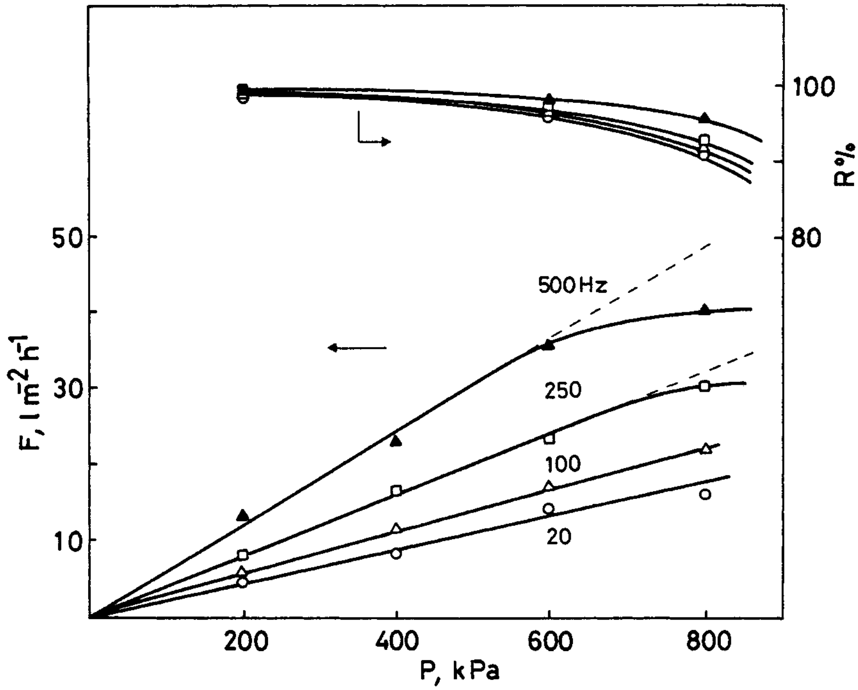

FIG. 7. Influence of the pressure (P) on the permeate flux (F) and rejection (R) at different frequencies. Vibration amplitude: 10^{-4} m.

The membrane area was only 0.0065 m^2. This fact caused a lower permeate flow and thus a higher measurement uncertainty. To overcome this drawback, it was decided to run most of the experiments at 800 kPa, which is about twice as high as the pressure usually employed in UF.

The influence of pressure on the permeate flux and rejection was explored. The results obtained are reported in Fig. 7. The almost linear trends of the curves recall those found in previous work (*14*). The shifts from straight lines at higher pressures are due to the "polarization" phenomena which are proportional to the flux crossing the membrane.

MATHEMATICAL MODEL

Thanks to mathematical software, it was possible to draw a simple equation representing, to a good approximation, the trend of the experimental data:

$$F = k_1 H P \delta^{0.5} + \mathrm{PA} \tag{2}$$

where F = permeate flux ($L \cdot m^{-2} \cdot h^{-1}$)
k_1 = constant = 0.008
H = vibration frequency (Hz)
P = pressure (kPa)
δ = vibration amplitude (m)
A = permeate flux attainable at frequency = 0 and pressure = 1 kPa (independently of rejection)

This equation fits well with the trend of experimental data, as can be seen in Fig. 3 where experimental points are superimposed on calculated values. Deviations from the theoretical trends are especially evident at high frequencies. This behavior is expected, because the relationship does not take into account the hydraulic head loss through the membrane itself. By increasing the flux, the concentration of the rejected oil on the membrane also increases, contributing to a decrease in the permeation speed. The final result is that the measured flux is less than the theoretical flux.

ENERGY CONSUMPTION

Two kinds of energy consumption were taken into account in order to evaluate the power requirement for running the vibrating module:

1. Energy necessary to feed the oil through the module (E_a)
2. Overall energy necessary to keep the membrane vibrating (E_b)

E_a was evaluated by taking into account the working pressure and the feed flux [it has been experimentally proved (5) that a recirculation flux 10 times higher than the permeate flux is enough to avoid a substantial concentration increase in the module]. As already demonstrated (5), the value of E_a is

$$E_a = 5.4 \times 10^3 P \qquad (3)$$

where E_a = pumping energy ($kWh \cdot m^{-3}$ of permeate)
P = pressure (kPa)

E_b is necessary to overcome the friction of mechanical parts and to maintain the motion of the membrane. This energy was evaluated by force measurements performed with a load cell inserted between the exciter and the module (see Fig. 2B). This kind of measurement involves some difficulties due to the overlapping of harmonics at certain frequency values. Nevertheless, the force necessary to shake the module has been found to vary according to the following equation:

$$N = k_2 \delta H^2 \tag{4}$$

where N = force (Newtons)
δ = vibration amplitude (m)
H = frequency (Hz)
k_2 = constant = 3.41

In Fig. 8 the force has been plotted vs δ at three different frequency values. From the force values the "true" energy applied to the module, and not only that consumed by the exciter used, can be calculated. By

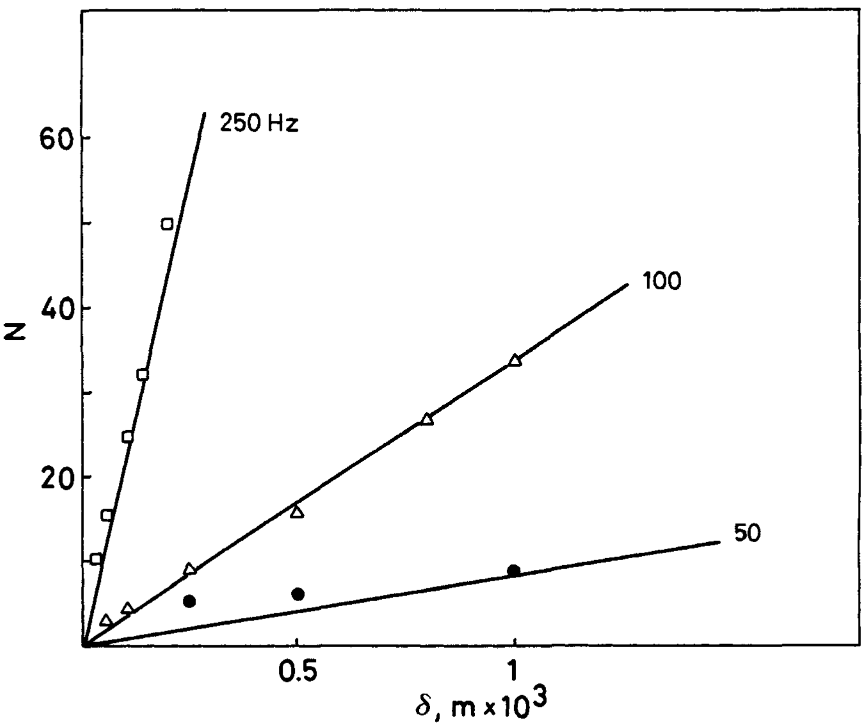

FIG. 8. Force (N) applied to the module as a function of vibration amplitude (δ) and frequency (H); P = 800 kPa. Lines are calculated by Eq. (4). Points are experimental.

summing up the two kinds of energy and relating the overall consumption to 1 m^3 permeate production, it is possible to draw the following relation:

$$E_t = E_a + E_b = \frac{kN(3.14)H\delta}{FS} + 0.0054P \qquad (5)$$

where E_t = energy necessary to produce 1 m^3 of permeate (kWh)
k_2 = constant = 3.41 (see Eq. 4)
S = membrane area = 0.0065 m^2

The other symbols have their usual meaning.

Equation (5) enables us to evaluate the overall energy consumption at any condition of frequency, amplitude, and pressure.

In Fig. 9 is plotted the influence of the vibration amplitude δ on the overall energy consumed to produce 1 m^3 of permeate at different frequencies. The plots show that E_t exponentially increases both with amplitude and frequency, and it increases more rapidly at high frequencies. This means that, above certain frequency values, the vibration energy is mainly spent to keep the support moving to overcome the increasing losses due to friction.

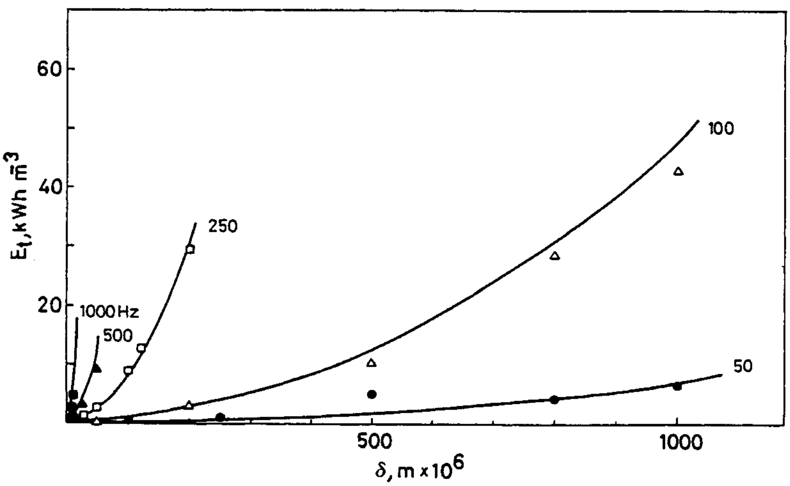

FIG. 9. Total energy consumption E_t ($kWh \cdot m^{-3}$) as a function of vibration amplitude (δ) and frequency (H); P = 800 kPa. The full lines are calculated by Eq. (5). Points are experimental.

CONCLUSIONS

Experimental tests performed by using the above-described vibrating module showed the following.

1. Vibrations applied to the membrane are successful in reducing the polarization layer and thus increasing the permeate flux during the UF process. The possibility that the vibrations of the system are responsible for breaking the oil droplets cannot be considered useful for enhancing the permeate flux because the smaller the droplets, the higher their penetration into the membrane pores. Experimentally, this means both flux and rejection reduction if the droplets are not swept away by the displacement (vibration) of the membrane surface.
2. As in the case of low-frequency vibrations, the permeate flux is influenced both by frequency and vibration amplitude. It is possible, at least for oil emulsions, to draw up an equation useful to calculate the permeate flux at any working condition for the frequency range of 50 to 1000 Hz and vibration amplitudes in the 0.01–10 mm range.
3. It is possible to evaluate the energy consumption required and to demonstrate that it increases with frequency. The energy requirements are nevertheless lower than those measured in the case of a mechanically driven module, working at lower frequency.

The collected results suggest that above a certain frequency, most of the required energy is spent to overcome the friction of the mechanical system and has little influence on performance membrane. As a consequence, it is worthwhile to try a different arrangement in order to minimize frictional energy losses. Industrial modules should have a more hydrodynamic configuration and a more rational exploitation of the vibrations. This could be achieved by applying the vibrations more closely to the membrane by means of a support capable of itself becoming a source of vibrations.

Study of the orientation of the vibrating field is also of interest. Until now, only longitudinal vibrations have been used by us, and the effect of radial vibrations of the membrane surface is still to be studied. This will be our purpose in future experimental investigations.

REFERENCES

1. H. K. Lonsdale, *J. Membr. Sci.*, *10*, 81 (1982).
2. G. Belfort, *Ibid.*, *35*, 245–270 (1988).
3. M. J. van der Vaal and I. G. Racz, *Ibid.*, *40*, 243–260 (1989).
4. M. Lopez-Leiva, in *Polymer Science and Technology*, Vol. 13 (A. R. Cooper, Ed.), Plenum, New York, 1980, p. 269.
5. F. Vigo, C. Uliana, and P. Lupino, *Sep. Sci. Technol.*, *20*(2&3), 213–230 (1985).
6. F. Vigo and C. Uliana, *Ibid.*, *21*(4), 367–381 (1986).

7. A. K. Bouzaka, M. Y. Jaffrin, and B. B. Gupta, *Proceedings of ICM 89, 1st International Conference on Inorganic Membranes,* July 3–6, 1989, Montpellier, France.
8. B. B. Gupta, L. H. Ding, and M. Y. Jaffrin, in *Progress in Artificial Organs* (Y. Nosé, C. Kjellstrand, and P. Ivanovich, Eds.), ISAO Press, Cleveland, 1986.
9. I. Mamo, N. S. Orlov, and Yu. I. Dytnerskii, in *Ochitska Stochnykh Vod Gazov. Vybrosov Fiz-Khim Metodami* (N. M. Korol'kov, Ed.), Rizh. Politekh. Inst., Riga, USSR, 1984, pp. 64–71.
10. I. Raben, in *Proceedings of the 1961 Heat Transfer and Fluid Mechanics Institute* (R. C. Binder, R. L. Mannes, H. Y. Yang, and M. Epstein, Eds.), 1961, pp. 90–99.
11. R. Lemlich, *Ind. Eng. Chem.*, *47*(6), 1175–1180 (1955).
12. J. A. Scanlan, *Ibid.*, *50*(10), 1565–1568 (1958).
13. S. M. J. Ali, H. N. Dawood, and A. Malhotra, *HTD (Am. Soc. Mech. Eng.), 116,* 47–53 (1989).
14. F. Vigo, C. Uliana, and E. Ravina, *Sep. Sci. Technol.*, *25*(1&2), 63–82 (1990).

Received by editor January 24, 1992
Revised June 24, 1992