Lait 80 (2000) 5–14

Original article

Flat ceramic membranes for the treatment of dairy products: comparison with tubular ceramic membranes

André GRANGEON, Philippe LESCOCHE*

TAMI Industries, ZA les Laurons, 26110 Nyons, France

Abstract — TAMI Industries has developed and commercialized since 1996 a new range of original ceramic membranes with a plane geometry. This type of membrane associates the interest of the weak hydraulic diameters to important values of thermal, mechanical and chemical resistance of ceramics. Shaped in a cassette form with open channels, these new membranes showed their efficiency in the environmental market. The purpose of this paper is to describe the standardization of milk proteins and the whey concentration studied to test these new products in the dairy industry. The result is expressed under the form of classic curves of the permeate flux in function of the VCF. These curves were established for velocities of 0.5 $m \cdot s^{-1}$, 1 $m \cdot s^{-1}$ and 2.5 $m \cdot s^{-1}$ and showed performances in the order magnitude of other types of membranes. By comparing with tubular products of TAMI industries, and on the basis of an industrial example (10 $m^3 \cdot h^{-1}$ of milk to process), two differences appeared: – on one hand, energy consumption by m^3 of permeate product were respectively for the plane geometry and the tubular geometry of 6 $kW \cdot m^{-3}$ and 9.4 $kW \cdot m^{-3}$; – on the other hand the cost of the system was 12 to 14 $kF \cdot m^{-2}$ for the tubular geometry and 8 to 10 $kF \cdot m^{-2}$ for the plane geometry. These differences were the consequence of the reduction of the hydraulic diameter. If one takes into account the shear constraint on the wall and the circulation speed as important parameters for the crossflow filtration, one observes that the diminution of the hydraulic diameter allows: – at constant velocity, to increase the shear constraint and to reduce energy. – at constant shear constraint, to reduce both the circulation speed and energy. In this case, membrane performances were identical and the equipment pricing became cheaper by reduction of the engineering costs. These comparisons were established between tubes and cassettes with opened channels and showed the interest to reduce the hydraulic membrane diameter what can simply be done by using the plane geometry. The particular case of a spacer, as a mean to reduce the hydraulic diameter, was not considered because of the complexity of the flow. Choosing open channels ceramic membrane plates allowed a global reduction of investment and functioning costs while keeping the interest of ceramics.

ceramic membrane / plate / tubular / dairy

* Correspondence and reprints. tami-info@tami-industries.com

1. INTRODUCTION

Ceramic membrane plates are now an industrial reality.

Two years of development with the help of a ANVAR program were necessary to introduce these new membranes. The original intellectual concept is protected by two international patents.

Strategically, TAMI Industries selected the environmental market to initiate the marketing of these membranes. The reasons of this choice was corresponding to an installed market of weak surfaces (low daily volume) and to the aggressiveness of products to process.

Currently, industrial installations are running for the effluent processing of:

– flexographic ink,

– mechanical industry degreasing baths,

– penetrant fluorescent test.

The proven performances of these membranes and their durability convinced TAMI Industries to introduce them to the dairy market.

This scope is currently occupied by ceramic or organic membranes and these last are available under different geometry according to Table I.

Ceramic materials do not allow to realise all geometry. The interest of the ceramic membrane plate is not to fill a supplementary square of the table above, but rather to offer the end user both the advantages of ceramic material and flat geometry. The main advantages are equipment modularity, the easiness for sanitation and the reductions of energy consumption and equipment cost. Modularity exists because ceramic membrane plates are set up according to a filter-press principle.

The objective of this study is to compare the energy consumption and the specific cost of the installation ($F \cdot m^{-2}$) of flat ceramic membrane against tubular ceramic membranes.

2. PRESENTATION OF PLATE CERAMIC MEMBRANES

Ceramic membrane plates are shaped as cassettes. They are composed of a compact block in which there are liquid channels in parallel and the input and output holes for retentate and permeate. Cassettes are set up inside a metallic cell that insures mechanical resistance to the pressure.

A metallic cell is defined by the maximum number of cassettes that it is possible to hold.

TAMI Industries commercializes actually three types of cassettes under the generic name KéRAM *INSIDE*:

– Mini KéRAM *INSIDE* for laboratory applications. The surface is 0.06 m^2.

– Centra KéRAM *INSIDE* for medium size applications. The surface is 0.25 m^2.

Table I. Different types of geometry for membranes.

Geometry		Materials	
		Ceramic	Organic
Tubular	Tubular		
	Hollow fiber	(Multichannels)	
Plate	Plate		
	Spiral		

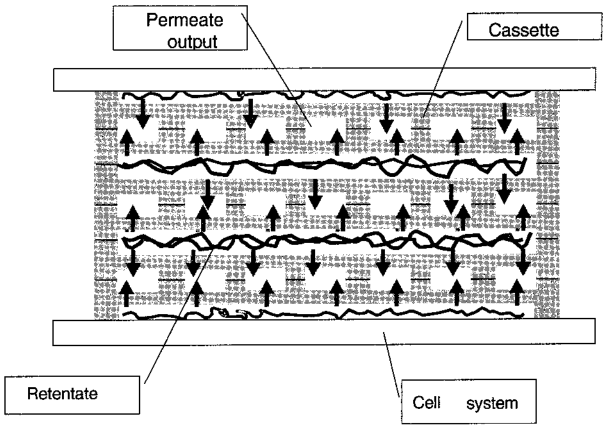

Figure 1. Cassette design.

– Maxi KéRAM *INSIDE* for industrial applications. The surface is 1 m^2.

2.1. Description of the Maxi KéRAM *INSIDE* cassette

A Maxi KéRAM cassette represents the association of 20 ceramic support plans. These supports are associated back to back and face to face as in Figure 1. The developed surface is 1 m^2 with a liquid channel height of 1.2 mm. The hydraulic diameter is therefore 2.4 mm.

2.1.1. Pressure resistant design

Permeate faces of ceramic support plans include bearings as counterthrust elements. Bearings of a support are in contact with the bearings of another support what allow to define:

– zones where the consequent mechanical effort to the pressure shows a constraint of compression. These zones correspond to bearings area,

– zones in which the consequent mechanical effort to the pressure shows a constraint of flexion. These zones correspond to volumes between bearings and they insure also the recuperation of the permeate flow.

For ceramics, flexion is a critical constraint due to risks of breakdown. The flat design supported with counterthrust elements eliminates rupture by flexion. In fact, knowledge of the constraint of flexion to rupture of the support material and its thickness allows to determine the distance between two bearings to avoid any breakdown in determined pressure conditions.

TAMI Industries have been awarded with an international patent registered on the no. 0 591 372 B1 on this design.

The cassette is then set up in a metallic cell as per Figure 2.

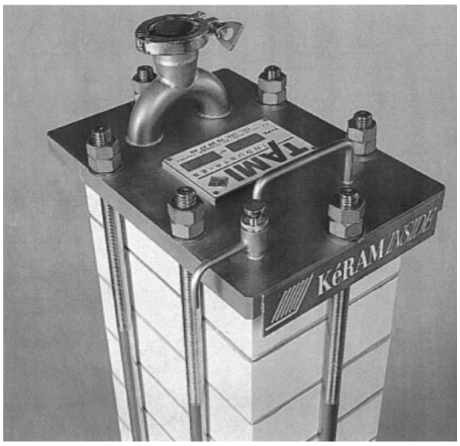

Figure 2. Cassettes inside cell system.

2.1.2. *Fluid circulation inside the cassette*

A cassette integrates liquid channels as well as entries and exits of the retentate and the permeate. This concept, protected by an other international patent registered on the no. 0 623 049 B1, allows equipment running at a constant flow due to high pressure capacity of the permeate compartment.

Figure 3 represents a top view of a ceramic membrane plate. It is composed of:

– external perimetric bearings. These bearings are located 0.6 mm higher than the central part. They include the four holes of permeate recovery,

– the central part with the two passages corresponding to the input and to the output of the liquid to process separated by a partition whose length is the two-thirds of the total length.

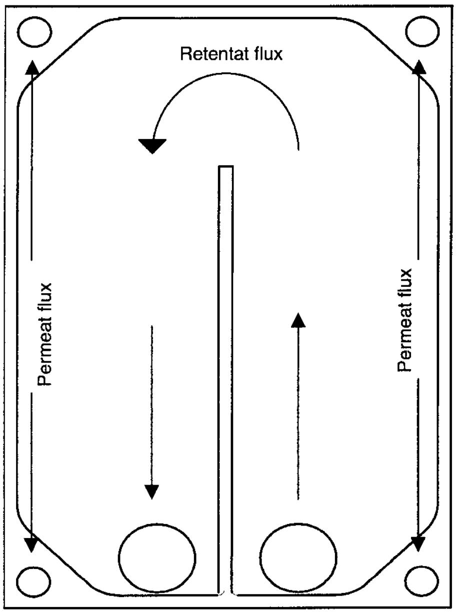

Figure 3. Fluid circulation.

This configuration has been computed numerically by an Institut de Mécanique des Fluides before its realisation. The aim was to optimize its shape to maximise speed homogeneity. This simulation included the division of the space in elements of volume which are used as support for the resolution of equations of the Mechanics of Fluids and the calculation of parameters such as hydrodynamic speed and pressure.

Figure 4 presents the distribution of speeds inside the central part for an average speed of 1.2 $m \cdot s^{-1}$ and for the optimised shape.

The scale of speeds shows the existence of strong speeds zones located to the input and the output of the fluid as well as to the extremity of the central partition.

For the rest of the volume, the speed variation are very weak.

Figure 5 presents the consequent pressure distribution to the circulation speed.

One observes that the pressure decreases regularly from the input to the output.

A cassette represents therefore the smallest number of liquid channels in parallel that one can set up in the cell system. For cassette Maxi KéRAM this number is eleven.

2.1.3. *Cassettes set up inside cell system*

Inside cell system the ceramic cassettes are set up in series or in parallel and according to the modularity their number can be variable. The number of cassettes some parallel defines the flux of the circulating pump.

The series number of cassettes in parallel defines the pressure of the circulating pump.

Several solutions are thus possible to define the circulating pump.

3. MATERIALS AND METHODS

3.1. Experimental pilot

It is composed by a feeding pump of 3 $m^3 \cdot h^{-1}$ under 4 bar, a circulating pump of 20 $m^3 \cdot h^{-1}$ under 2 bar that allows a maximum of 15 cassettes (15 m^2) under the

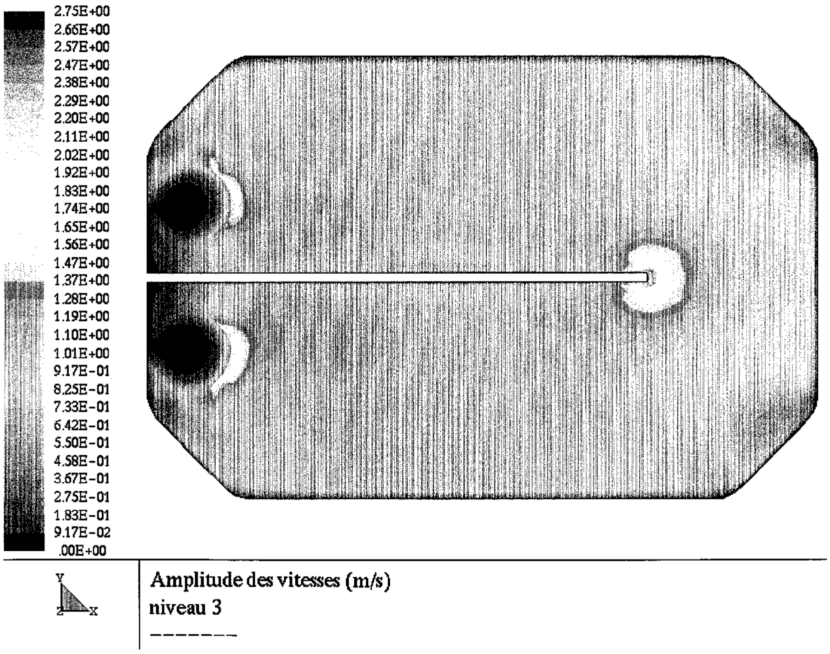

Figure 4. Speed distribution inside the channel.

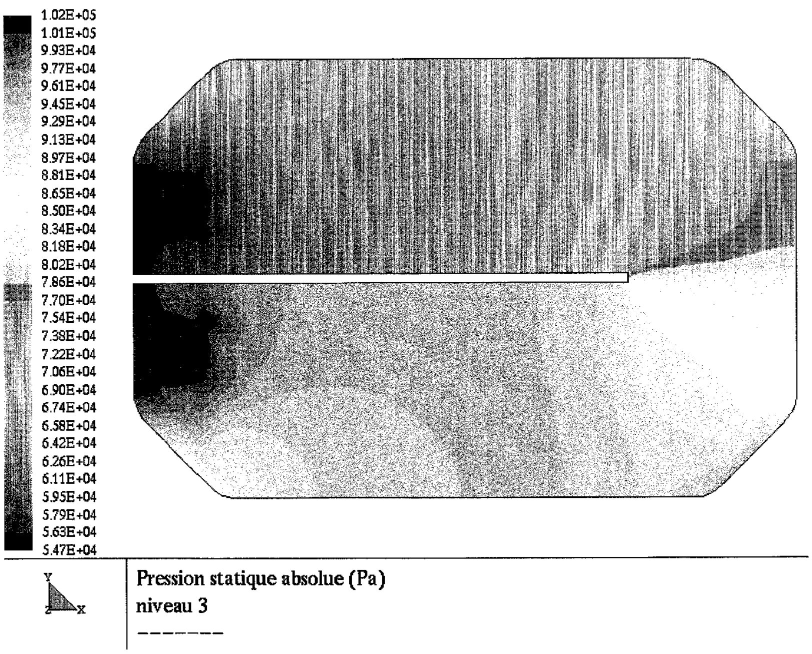

Figure 5. Pressure variation inside the channel.

configuration of 5 series of 3 cassettes in parallel.

This configuration correspond to a quarter of a stage in which we have normally a circulating pump of 80 $m^3 \cdot h^{-1}$ for a surface of 60 m^2.

The pilot is equipped to read:

– cassettes downstream and upstream pressures,

– flux in the loop and permeate.

The speed is regulated by the intermediary of a velocity valve at the downstream of the circulating pump.

Variations of pressure are obtained by valves on the output of retentate and permeate. The pilot possesses more over a heat exchanger and a prefilter upstream of the feeding pump.

It is connected to a tank of 50 L fed in continuous by the dairy product to process.

3.2. Methodology

The objective is to compare the performance of ceramic plate membranes against ceramic tubular membranes. For these last, the performances are well known and not studied in this paper. Thus, for milk (whole and skimmed) and sweet whey, the variable parameters examined are:

– the circulation speed,

– the volumetric concentration factor,

and the constant parameters are:

– the pressure at 4 bar,

– the temperature at 50 °C,

– the cut-off membrane at 150 $kg \cdot mol^{-1}$.

These results allow optimisation of circulating flux values, the corresponding pressure drops and working pressures, which in turn define circulating and feeding pumps. Energy consumption and installation costs of systems made of flat vs. tubular ceramic membranes are calculated following an example of dairy product treatment by a 10 $m^3 \cdot h^{-1}$ plant.

4. RESULTS

4.1. Milk standardization

4.1.1. On pasteurized skim milk

Figure 6 shows the influence of the circulating speed and the volumetric concentration factor (VCF) on the permeate flux.

The permeate flux varies with speed in almost a linear fashion. It depends also on the volumetric concentration factor.

The permeate concentration in soluble proteins is 0.4 $g \cdot L^{-1}$ for a volumic concentration factor of 3 which means a retention of 98%.

For this type of milk, the permeate flux obtained on a tubular ceramic membrane with a 3.5 mm hydraulic diameter is in the order 40 $L \cdot h^{-1} \cdot m^{-2}$ for a volumetric concentration factor of 3 and a speed of 4.5 $m \cdot s^{-1}$. The corresponding circulating flux for one element of 0.35 m^2 is 4.05 $m^3 \cdot h^{-1}$ and the drop pressure is 1.3 bar.

For ceramic membrane plates of 1 m^2, this permeate flux is reached at a speed of 3.3 $m \cdot s^{-1}$ with a drop pressure of 1.1 bar. The corresponding circulating flux is 12 $m^3 \cdot h^{-1}$.

The energy difference for cross flow filtration between flat ceramic membranes and tubular ceramic membranes can be expressed by the ratio of the products of circulating flux to the pressure drop for each type of membrane and for the same surface.

For a same permeate flux, flat ceramic membranes consume therefore 20% less energy for cross flow filtration than tubular ceramic membranes.

But, the choice of the recirculating speed also depends on economic factors.

As mentioned above (see 2.1.3) several solutions are possible to define the circulating pump.

Schematically, for a same volume to process, it is possible to realize installations with either high speed and weak surfaces with a high cost for engineering or installations

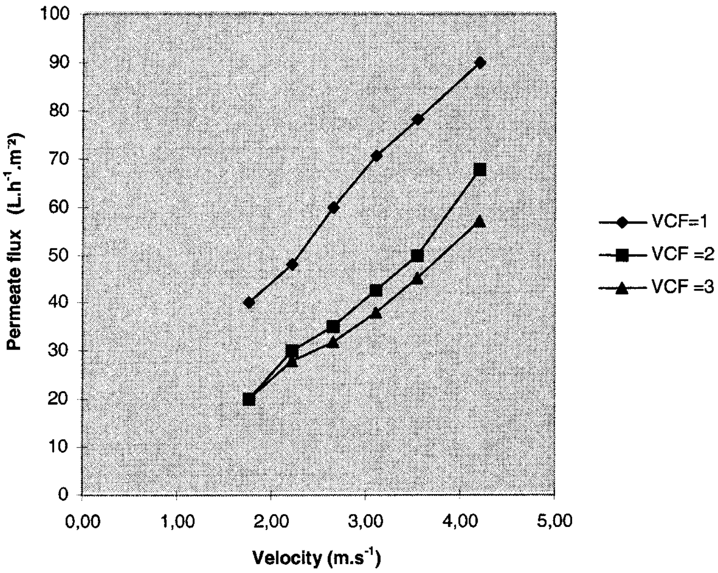

Figure 6. Incidence of the speed and VCF on the permeate flux of skimmed milk.

or weak speed and high surfaces but whose cost of the engineering is far weaker.

Economic calculations show that it is often advantageous to use low recirculating speeds.

In the case of milk, the selected circulating speed is 2.6 m·s^{-1}. The loss of performances is in the order 20%, but the energy consumption for cross flow filtration is 1.57 time lower than for tubular ceramic membranes.

4.1.2. On whole milk

The recirculating speed is fixed at 2.6 m·s^{-1}.

Figure 7 hereafter shows values of permeate flux in function of the volumetric concentration factor.

In comparison with skimmed milk, the permeate flux is lower which is a normal result.

The retention rate for soluble proteins is the same as for skimmed milk: 98%.

The recirculating speed is fixed at 2.6 m·s^{-1}.

Results are presented in Figure 8.

For a volumetric concentration factor of 10 the permeate flux is 42 L·h^{-1}·m^{-2} and the retention rate is 97%.

5. ECONOMIC COMPARISONS BETWEEN FLAT AND TUBULAR CERAMIC MEMBRANES

This comparison is done using an example a volumetric concentration factor of 3 with an hourly volume of 10 m^3 of pasteurized skim milk. The production time is 8 h.

Experimental conditions are the following:

Experimental Parameters	Tubular membranes	Flat membranes
Speed (m·s^{-1})	4.5	2.6
Membrane hydraulic diameter (mm)	3.5	2.4
Cut off (kg·mol^{-1})	150	150
Temperature (°C)	50	50
Average pressure (bar)	4	4

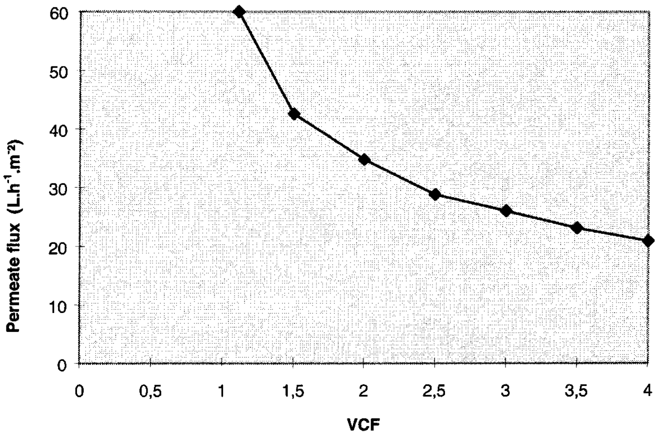

Figure 7. Incidence of VCF on the permeate flux of whole milk.

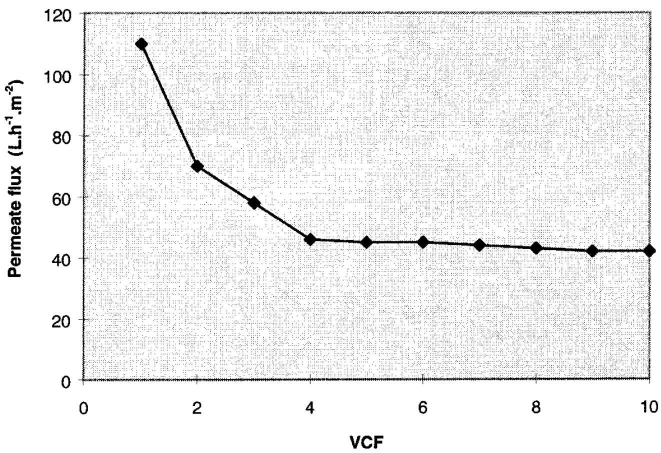

Figure 8. Incidence of VCF on the permeate flux of whey.

The presentation of equipment system is developed in Table II.

This table shows respective differences between installations made from tubular ceramic membranes or flat ceramic membranes.

Due to the difference of circulating speeds between tubular membranes and plate these last:

– need more surface,

– circulating pumps far weaker with two main consequences, on the one hand on installation costs related to prices of pipes, valves, instruments and pumps and on the other hand over energy consumed.

If one subdivides the cost of an installation in two parts that are respectively membranes

Table II. Comparison between flat and tubular ceramic membranes.

Description of the installation	Tubular membranes	Flat membranes
Area (m^2)	154	180
Stage number	2	2
Stage 1 area (m^2)	77	90
Stage 2 area (m^2)	77	90
Energy consumed (kW)	62	40
Energy consumed by m^2 of membrane ($kW \cdot m^{-2}$)	0.4	0.21
Energy consumed by m^3 of permeate ($kW \cdot m^{-3}$)	9.4	6
Installation cost (MF)	2.2	1.5
Specific cost ($kF \cdot m^{-2}$)	14	8.8

and the equipment (pumps, pipings, valves, instruments of measure, electricity, automatism, regulation), one observes:

– for installations based on tubular ceramic membranes, membranes represents approximately 40% and the equipment 60%,

– for installations based on flat ceramic membranes, membranes represents approximately 60% and the equipment 40%.

For a same service, the flat geometry therefore allows:

– to reduce costs,

– to increase the proportion of membranes in the cost of the installation.

6. DISCUSSION AND CONCLUSION

By using the following relations:

$$\tau_w = \frac{R \cdot \Delta p}{2 \cdot L}$$

$$\Delta p = \lambda \cdot \frac{V^2 \cdot L \cdot \rho}{2 \cdot \Phi}$$

$$\lambda = A \cdot Re^{-x}$$

$$Re = \frac{\rho \cdot V \cdot D}{\eta}$$

in which:

τ_w = wall shear constraints,
R = membrane hydraulic radius,
L = membrane length,
Δp = membrane pressure drop,
λ = friction coefficient,
V = circulating speed,
ρ = volumic mass,
η = dynamic viscosity,
Φ = membrane hydraulic diameter,
Re = Reynolds number,
A = coefficient,
x = exponent of $Re \cdot x$ depends on the channel shape.

It is possible to show that these differences are the consequence of the diminution of he hydraulic diameter.

For two membranes with:

– the same material,

– the same length,

– the same channel shape,

– different hydraulic diameters with index 1 > index 2.

We have:

$$\frac{\tau_{w_1}}{\tau_{w_2}} = \frac{V_1^{\,2-x}}{V_2^{\,2-x}} \times \frac{\Phi_2^{\,x}}{\Phi_1^{\,x}}$$

that means if:

$$\tau_{w_1} = \tau_{w_2} \Rightarrow V_2 < V_1$$

or if:

$$V_1 = V_2 \Rightarrow \tau_{w_1} < \tau_{w_2}.$$

For the energy:

$$\frac{W_1}{W_2} = \frac{V_1{}^{2-x}}{V_2{}^{2-x}} \times \frac{\Phi_1{}^{1-x}}{\Phi_2{}^{1-x}} \text{ and } \frac{W_1}{W_2} = \frac{\tau_{w_1}}{\tau_{w_2}} \times \frac{\Phi_1}{\Phi_2}$$

that means if:

$$\tau_{w_1} = \tau_{w_2} \Rightarrow W_2 < W_1$$

or if:

$$V_1 = V_2 \Rightarrow W_2 < W_1.$$

Indeed, if one considers two membranes whose difference is only the hydraulic diameter, one shows that when this last decreases:

– if the circulation speed is the same for the two membranes, the membrane whose hydraulic diameter is the smallest possesses the higher shear constraint and the weakest energy of cross flow filtration,

– if the shear constraint is the same for the two membranes whose hydraulic diameter is the smallest possesses the lowest circulating speed and the weakest energy for cross flow filtration.

These relationships have to be compared with the results obtained on skim milk where one observes same performances between tubular ceramic membranes and flat ceramic membranes with a lower circulating speed and hydraulic diameter for these last.

It has not been possible to compare experimental wall shear constraints for the two types of membranes above because the fluid path in the case of flat membrane comprises a 180° bench. In these conditions, the length of the fluid way is included between the geometrical value and the equivalent hydraulic value of this fluid way.

This result shows nevertheless the interest to reduce the hydraulic membrane diameter which is allowed in a simple manner using the flat geometry. The particular case of a spacer, that is a means of reducing the hydraulic diameter has not been processed because of the complexity of the flow. Also, the choice of flat ceramic membrane with open channels allows a global reduction of investment and operating costs while keeping the interest of ceramics.