CHAPTER 4:

Design and performance characterization of a new shear enhanced module with inbuilt cleaning arrangement

Shear enhanced membrane modules are being popular for yielding high permeate flux in almost all the membrane filtration processes due to the high shear rate they are capable to generate at the membrane surface. In this work, the design of a new shear enhanced module with unique hydrodynamic cleaning facility has been proposed. The device, presently in lab scale was named as Spinning Basket Membrane (SBM) module considering its inherent structural similarity with the well known Spinning Basket Reactor. Aqueous solution of Polyethylene glycol was chosen as a test fluid for the present study.

The module was characterized under different parametric conditions of transmembrane pressure (TMP), feed concentration \( C_0 \) and rotational speed of the basket \( \Omega \). It was observed that with its inbuilt cleaning facility the module was able to restrict the flux decline within 15% of its corresponding start up value even after 21 h of continuous run, whereas the maximum initial flux was as high as 612 L m\(^{-2}\) hr\(^{-1}\).

Considering the performance of the module, it may be concluded that this module could be scaled up for nearly uninterrupted industrial operation with reduced number of chemical cleaning, which is rare in membrane industry till date.
4. Introduction

Over the last two decades membrane technology has developed enormously. This is expressed in the vast amount of research, which has gone into developing the right membrane type and module for different kinds of separation process, developing new processes as well as searching for the best possible circumstances for separation. The effort has resulted in present day commercialization of ultrafiltration (UF), microfiltration (MF) or reverse osmosis (RO). However, with its entire potential still the membrane based processes are not used on a much larger scale due to massive flux decline during the process (Belfort et. al., 1994; Moure et. al., 2006; Kobayashi et. al., 1996; Tarleton and Wakeman, 1993). The permeate flux is primarily affected by the phenomenon of membrane fouling (i.e. solute built up at the membrane surface and subsequent adsorption), which may be reversible (primarily known as concentration polarization) as well as irreversible in nature. Moreover, the reversible concentration polarization effect can lead to irreversible fouling (solute adsorption, gel layer formation, etc.) reducing the effective lifetime of the membrane (Sablani et. al., 2001). Fouling can be reduced by proper choice of membrane/solute combination or by using suitable pretreatment and by exploiting all possible means to reduce solute built up at the membrane surface (Chen et. al., 1997). In the late 1960 cross flow module had been developed with a basic objective to restrict membrane fouling. In a standard cross flow module high feed velocity induced membrane shear is capable of disengaging the rejected solute, but at the same time it causes a large axial pressure drop leading to a ‘non-optimal membrane utilization’ (Jaffrin, 2008). On the other hand, as the membrane shear is entirely dependent on the feed flow rate the degree of solute built up is generally higher for a small capacity module otherwise high retentate flow rate will demand higher energy consumption by the pump.

In order to introduce an independent membrane shear in relation to the feed flow rate dynamic or shear enhanced module was developed in the mid 1970. The first commercialized shear enhanced module was a Couette flow type with a cylindrical membrane rotating inside a concentric cylindrical casing (Kroner and Nissingen, 1988; Holeschovsky and Cooney, 1991). The module was successfully applied for plasma collection from human blood. Later different shear enhanced modules were developed and successfully used for a wide range of practical applications. Rotating disk module in which a multi-disk mounted shaft rotates between fixed
membranes was introduced by ABB Flowtek, the optifilter CR and presently being used primarily for treating paper-pulp effluents and for pigment recovery (Lee et al., 1995). In addition to the rotating disk system, rotating membrane based multiple shaft disks (MSD) separator has been launched commercially by Aaflowsystems (Aalen-Eisingen, Germany) in which multiple ceramic membranes mounted parallel shafts arranged in a circle are placed in a cylindrical casing (Feuerpeil et al., 2003). The partial overlapping membranes mounted on two adjacent shafts rotate in the opposite direction with respect to each other in order to intensify the velocity gradient and hence the shear on the membrane surface. Performance characteristics of standard MSD pilot in microfiltration of CaCO₃ suspension have been reported by Ding et al., 2006. The results of the investigation show that MSD pilot is capable of producing high permeate flux at highest rotational speed and transmembrane pressure. In a separate study effect of membrane overlapping on the performance of MSD pilot has been investigated by Jaffrin et al., 2006. It is reported that the membrane overlapping in general increases the permeate flux, but the rate of increase decreases with increasing rotational speed of the pilot. On the other hand, performance studies of a modified MSD pilot with overlapping ceramic membrane and non-permeating disks rotating independently has also been reported (He et al., 2007). The corresponding results show that for vane fitted disks permeate flux increases significantly in comparison to the standard MSD pilot and at the same time energy consumption per unit volume of the permeate reduces significantly. Recently, the performance characteristics of nylon membrane fitted modified MSD pilot has also been reported though the specific energy consumption in polymeric membrane MSD was found to be much higher than their ceramic counterpart (Tu and Ding, 2010).

But unfortunately with all its advantages the transient decline of permeate flux from start up to steady state cannot be eliminated to an appreciable extent even in the most advanced shear enhanced module. Even a standard rotating disk membrane module, in which a rotating membrane is placed closely to a counter rotating stirrer in a cylindrical casing suffers from nearly 30% reduction of initial permeate flux (Sarkar and Bhattacharjee, 2008). And the reduced permeate flux in any standard module can be only recovered by through chemical cleaning, which means an interruption in the normal run. That is why membrane based systems operate in a cyclic mode, where cleaning runs alternates with the normal run (Zondervan and Roffel, 2007). Once again, it is to be noted that cleaning operation may not be fully efficient from the
Design and performance characterization of a new shear enhanced module with inbuilt cleaning arrangement

perspective of total recovery of the initial permeate flux and frequent cleaning of membranes is costly and may damage the membrane material, which results in reduced membrane life and selectivity (D’Souza and Mawson, 2005; Tran-Ha et al., 2002; Blanpain-Avet et al., 2009). Time/duration of the cleaning run (tc) is also an important parameter to be optimized. Several researchers have reported that cleaning time has a beneficial effect on flux recovery (Mohammadi et al., 2002; Madaeni et al., 2004; Kazemimoghadam and Mohammadi, 2007), though the effect of an increasing cleaning time was found to be decreasing gradually (Madaeni and Daneshvar, 2004).

So in general it becomes clear that if a shear enhanced module could be designed, which has the ability of self cleaning without using any external chemical agent it would be highly advantageous not only from the objective of minimizing the operating cost but also in relation to have an uninterrupted normal run. As in this type of module the gap between two successive chemical cleaning would be much higher than the existing modules, even if it is a shear enhanced. The present work has been undertaken in an attempt to design and to characterize the performance of a new shear enhanced device named as the Spinning Basket Membrane (SBM) module considering its structural similarity with the well known Spinning Basket Reactor. In the present study, the operational characteristics of the designed SBM module have been reported as a function of basket rotational speed, applied transmembrane pressure (TMP) and feed concentration in ultrafiltration of polyethylene glycol 6000 (PEG 6000) solution using polyethersulfone (PES) membrane of 5000 Da molecular weight cut-off. In addition to the permeate flux based characterization the respective role of different operational parameters (Ω, C₀, and TMP) has been also investigated in the power consumption pattern of the proposed module.

4.1. Materials and methods

4.1.1. SBM module

As stated earlier, the proposed module has been conceptualized to be like a Spinning Basket Reactor with flat membranes (each of dimension 65×145 mm² with an effective area of 55×130 mm²) fitted on alternate sides of adjacent radial arms, while the other side remains impermeable.
Design and performance characterization of a new shear enhanced module with inbuilt cleaning arrangement as shown in Fig. 4.1. The hollow basket with four radial arms (which may be increased in a scaled up module) was mounted on a central hollow shaft fitted with a pulley drive.

![Schematic diagram of the Spinning Basket Module](image)

**Figure 4.1.** Schematic diagram of the Spinning Basket Module (insert showing the photograph of the spinning basket)

The whole system with suitable sealing arrangement was placed in a stainless steel cylindrical tank fed by a triplex piston pump. In order to enhance the shear rate on the membrane surface at the basket was subjected to high speed rotation in the direction of the membrane surface (outward normal to the membranes). The power requirement for the high speed rotation was provided by a three phase induction motor with a belt pulley drive connected to the central shaft of the SBM module. The clearance between the tip of the radial arms and the cylindrical housing was 6 mm, which causes additional dynamic pressure built up on the membrane surface. As a result the effective transmembrane pressure becomes higher than the applied transmembrane pressure (TMP) developed by the pump. However, the primary advantage of small clearance can be explained from the perspective of vortex like circulation flow generated between two adjacent arms. Because of the high velocity circulation of the feed solution accumulated solutes on the membrane surface were swept away leading to a reduced degree of polarization. Though we have not estimated the shear rate in the module, but it is expected to be a monotonically increasing function of basket’s rotational speed.
With all its shear enhancement it is obvious that still the proposed module will suffer from the drop of transient permeate flux from the start up to the respective steady state as is the case of any membrane module irrespective of whether it is shear enhanced or not. Here comes the uniqueness of the proposed module. Once the flux reaches its steady state the basket is to be rotated in the reverse direction (in the direction normal to the impermeable side of the radial arms) after releasing the applied transmembrane pressure to atmospheric pressure by operating the back pressure regulator (BPR) fitted in the retentate line. As a result a local vacuum of \( \frac{1}{2} \rho V_o^2 \) will be created on the membrane surface, so that the effective absolute pressure on the retentate side becomes \( p_{\text{atm}} - \frac{1}{2} \rho V_o^2 \), whereas on the permeate side it will remain atmospheric. Because of the counter rotation induced pressure difference the accumulated solute is expected to be disengaged from the membrane thereby reducing the hydraulic resistance of the same. This will result in a recovered permeate flux in the next normal run.

For the present work, the lab scale SBM module made of SS316 was manufactured by Gurpreet Engineering Works, Kanpur, UP (India) as per the specified design. The schematic of the complete filtration bench is depicted in Fig. 4.2. The induction motor was fitted with a variable speed drive and a reversing switch for efficient speed control and reversal of the rotational direction respectively.

### 4.1.2. Material
Polyethylene glycol (PEG-6000, AR grade) of molecular weight range of 5000–7000 dissolved in water was used as feed solution and was obtained from Merck, India. Moist PES membrane (asymmetric, molecular weight cut-off: 5,000 Da) was obtained from Koch Membrane Systems (USA). The rectangular membrane was operable in the pH range of 2-10.

### 4.1.3. Analysis
Solution concentrations were measured with a refractometer (Brix 0-30%, Erma Inc., Tokyo, Japan). The density and viscosity were determined by solution concentration at 303 K.
4.1.4. Design of experiment

In order to explore the operational characteristics of the proposed module experiments were designed in such a way so that the effect of three process parameters, namely the applied transmembrane pressure (98.0, 196.1, 392.3 and 588.4 kPa), feed concentration (10, 20, 30 and 40 kg m\(^{-3}\)) and rotational speed (10.47, 20.95, 31.4 and 41.9 rad s\(^{-1}\)) could be investigated. Any two of the parameter were kept constant while the third one is varied in order to get the actual nature of the dependence. A constant retentate flow rate of 10\(^{-4}\) m\(^3\) s\(^{-1}\) was maintained for all the experimental runs. In cleaning run, the module was operated with the same rotational speed (in opposite direction) as that of the corresponding normal run with released transmembrane pressure (TMP=0) for a duration of 300 s. It is to be noted that the speed as well as the duration of the cleaning run was totally arbitrary. After each cleaning run the module was again subjected to normal run. In the present study, the duration of each normal run was fixed to be of 2 h (the duration was determined by the time required for the permeate flux to reach its steady value). It is also to be noted that each continuous experiment marked by a definite TMP, \(\Omega\) and \(C_0\) consists of ten normal runs intervened with nine cleaning runs, i.e., with a total duration of 21 h.
In order to compare the performance of SBM with other standard shear enhanced modules, experiments with the same membrane-solute combination (PES/PEG-6000) have been performed in Single Stirred (SS) and Rotating Disk Membrane (RDM) modules. The detailed specifications and the geometry of these two well-known shear enhanced modules are described elsewhere (Sarkar and Bhattacharjee, 2008). For the RDM module, the membrane speed was fixed at its highest permissible limit i.e. at 62.5 rad s\(^{-1}\). It is also to be noted that the experiments of SS and RDM modules have been conducted at the same TMP, \(\Omega\) (for both of the modules the stirrer speed was chosen to be the parameter equivalent to the basket rotation speed, \(\Omega\) for the sake of comparison) and \(C_0\) as that of the proposed SBM module.

### 4.1.5. Procedure

For the present system four rectangular membranes were fixed on four rectangular porous supports on the alternate faces of four radial arms. In order to overcome compaction effect of the membranes, the module was pressurized with distilled water for at least 3 h at a transmembrane pressure of 600 kPa, which was higher than the highest operational pressure. This was followed by actual experiments. In order to determine the transient permeate flux 10 cm\(^3\) of permeate was collected in a measuring cylinder and the time for collection was recorded. Each normal run was continued until at least two successive flux reading was nearly equal. As stated earlier each normal run was followed by cleaning run with duration of 300 s. Once an experiment with a tentative duration of 21 h was over, all the four rectangular membranes were thoroughly cleaned with distilled water at least for 2 h to remove any deposit. The water flux was checked again to detect any variation in the hydraulic resistance of the membrane. The same procedure was repeated for each experiment with fixed TMP, \(\Omega\) and \(C_0\). It is also to be noted that for the purpose of comparison similar experimental procedure was followed for the other two mentioned shear enhanced modules (Sarkar and Bhattacharjee, 2008).

### 4.2. Results and discussion

#### 4.2.1. Variation of the permeate flux with transmembrane pressure (TMP)

At a constant TMP, the unsteady state permeate flux presented an initial decay from high initial value during the first 1.5 h of the normal run, after which it has attained a steady state value. Because of this as stated earlier each normal run in the present study was continued for
Design and performance characterization of a new shear enhanced module with inbuilt cleaning arrangement
duration of 2 h. The variation of permeate flux with time for different TMP (but at fixed feed concentration and rotational speed) for the first three normal runs is shown in Fig. 4.3. The figure clearly indicates that for the first three normal runs the average drop of permeate flux from the initial condition to the steady state (described as $\frac{J_{\text{initial}} - J_{\text{steady}}}{J_{\text{initial}}} \times 100$) was nearly 17% for different TMP.

![Figure 4.3. Variation of the unsteady permeate flux with time under the condition of different TMP for the first three normal runs](image)

The result was expected because over the same duration the effective thickness of the concentration-polarization layer has increased from zero to some steady value. According to the well known osmotic pressure model the growth of the concentration-polarization layer increases the osmotic pressure differential between the retentate and the permeate side of the membrane resulting a reduced permeate flux (Kedem and Katchalsky, 1961). On the other hand, Fig. 4.3 also reveals that the transient as well as the steady permeate fluxes during any normal run increased significantly with the increase of TMP. In order to be more informative variation of the steady flux for the first normal run i.e. the flux just before the first cleaning run with respect to the applied TMP at a different rotational speed ($\Omega$) is shown in Fig. 4.4. The steady flux was observed to increase with TMP almost linearly at different $\Omega$. But the rate of change was more intense on the higher side values of rotational speed. It may be attributed to the fact
Design and performance characterization of a new shear enhanced module with inbuilt cleaning arrangement

that at low $\Omega$, high TMP condition the effect of concentration polarization was severe because of high convective flow towards the membrane due to high TMP and low shear rate, subsequently lower rate of solute disengagement from the membrane surface due to low $\Omega$.

![Figure 4.4](image)

**Figure 4.4.** Variation of steady permeate flux (as obtained at the end of first normal run) with TMP for different rotational speed ($\Omega$)

Accordingly the rate of flux enhancement with TMP was lowered. On the other hand, at high $\Omega$ the concentration built up on the membrane surface was restricted to a large extent because of enhanced shear rate due to the vigorous circulation flow between two successive radial arms of the module. As a result the rate of flux enhancement as well as the flux itself was enhanced with TMP. Similar trend was reported by Luo et al. (Luo et al., 2010) in nanofiltration of dairy wastewater using a standard Rotating Disk Membrane (RDM) module.

**4.2.2. Cleaning run performance for normal runs conducted at different TMP**

It is to be noted that all the cleaning runs were conducted at the same rotational speed as that of the corresponding normal run with zero transmembrane pressure. The Fig. 4.5 shows the variation of the regenerated permeate flux after every cleaning run for normal runs conducted at different TMP. After the first cleaning run the average recovery of permeate flux (described as $\frac{J_{\text{regenerated}} - J_{\text{steady}}}{J_{\text{steady}}} \times 100$) was nearly 19%, which means the regenerated flux was nearly 96%
Design and performance characterization of a new shear enhanced module with inbuilt cleaning arrangement of the initial flux, whereas the corresponding average steady flux, obtained at the end of the first normal run was 82% of its initial counterpart.

Now if the variation of the regenerated permeate flux from one cleaning run to the next is investigated, as shown in Fig. 4.5 it becomes clear that after 9th cleaning run, the average value of the regenerated flux was more than 90% of the average initial flux (i.e. the average flux at the beginning of the first normal run) for different TMP. This marks a unique feature of the proposed module and probably no existing module can restrict the drop of permeate flux within 10% of the initial value for a total effective run time duration (total normal run time in an experimental run) of 19 h, which corresponds to nine normal runs with nine intermediate cleaning runs.

Regarding the cleaning mechanism, it is to be noted that in cleaning run due to high speed rotation of the basket in the direction reverse to that of corresponding normal run a local vacuum of \( \frac{1}{2} \rho V_o^2 \) was created on the retentate side of the membrane which triggers the disengaging action. But if the solute adsorption on the membrane surface is irreversible (which is definitely not the case for PEG 6000/ PES combination) and the heat of adsorption is high like...
Design and performance characterization of a new shear enhanced module with inbuilt cleaning arrangement

The case of protein ultrafiltration, the created vacuum in the cleaning run may not be sufficient to disengage the adsorbed solute. In that case, the cleaning run would not remain as efficient as in the present case; still the module is expected to function well from the viewpoint of shear enhancement.

4.2.3. Variation of permeate flux with feed concentration

Variation of the permeate flux with time for four different feed concentrations over the first three successive normal runs are as shown in the Fig. 4.6. Here the initial flux values were same for four concentrations indicating no polarization effect as such. Once again, the flux behavior was exactly consistent with the trends predicted by osmotic pressure model.

As the initial osmotic pressure differential $\Delta \pi = \pi_r - \pi_p$ was very small in comparison to the applied transmembrane pressure the initial flux, $J(0)$ became independent of the feed concentration as $J(0) = \frac{TMP}{\mu R_m}$, where $R_m$ is the hydraulic resistance of the membrane. With time osmotic pressure differential was increased due to accumulation of the rejected solute on the retentate side leading to a reduced driving force ($= TMP - \sigma \Delta \pi$) and hence a reduced permeate

Figure 4.6. Variation of the unsteady permeate flux with time under the condition of different feed concentration ($C_0$) for the first three normal runs.
Design and performance characterization of a new shear enhanced module with inbuilt cleaning arrangement

flux. So the initial sameness of the permeate flux was lost and the relative difference was increased unless and until the steady state was reached, where osmotic differential has leveled off to definite but different values marked by different feed concentration. In the first normal run, the initial flux has decreased by 14% for a feed concentration of 10 kg m\(^{-3}\), where as a 25% decrease was observed for the highest feed concentration of 40 kg m\(^{-3}\). This was pretty obvious as \(\Delta \pi\) is a monotonically increasing function of feed concentration.

In the cleaning run a better recovery was observed for the cases of high feed concentration. A closer investigation reveals that 21% flux recovery was achieved after the first cleaning run for normal run conducted with a feed concentration of 40 kg m\(^{-3}\); whereas the same was only 12% for 10 kg m\(^{-3}\). This establishes that the disengaging capacity of the cleaning run was practically independent of the amount of accumulated solutes at least for the specific feed concentration range, which also indicates a complete reversibility of solute adsorption for the present solute-membrane combination during normal run. The variation of the regenerated flux with different cleaning runs has not been shown separately because the trend is expected to be similar as shown in Fig. 4.

4.2.4. Variation of permeate flux with rotational speed and the characteristics of the subsequent cleaning runs

The variation of permeate flux with time for different rotational speed of the basket (\(\Omega\)), but under constant TMP and feed concentration for the first three normal runs is shown in Fig. 4.7. Here contrary to Fig. 4.6 the initial fluxes were different for different rotational speed. This can be explained from the perspective of increasing dynamic pressure with rotational speed. As a result the effective transmembrane pressure became \(TMP + \frac{1}{2} \rho V_\theta^2\), where \(V_\theta\), the tangential velocity is directly proportional to \(\Omega\). So in general a higher permeate flux was expected for the case of a high rotational speed run. In the first normal run 115% steady flux enhancement was observed for a rotational speed change from 10.47 to 41.9 rad s\(^{-1}\). Whereas for the second and the third normal runs the changes were 117% and 113% respectively for the same change of rotational speed. This indicates that the effect of rotational speed was practically independent of the number of normal runs at least for first three runs.
Figure 4.7. Variation of the unsteady permeate flux with time under the condition of different rotational speed ($\Omega$) for the first three normal runs

On the other hand, Fig. 4.7 once again reveals the efficient characteristics of the cleaning runs. As it can be clearly observed from the figure that on an average the flux recovery was nearly 18%, which means that for all the three normal runs the average regenerated flux was roughly 98% of the initial flux values of the corresponding runs. The details of the cleaning run characteristics for normal runs performed at different rotational speeds has been shown in Fig. 4.8. It is to be noted that each cleaning run was conducted at zero TMP and with the same rotational speed as that of the corresponding normal run. The regenerated permeate flux after 9th cleaning run was observed to have nearly the same kind of dependence on the rotational speed as the initial flux. A closer investigation reveals that for an increase of rotational speed from 10.47 to 41.9 rad s$^{-1}$ the regenerated permeate flux after 9th cleaning run was increased by 120%. In order to analyze the cleaning run performances it is to be noted that regenerated permeate flux after the 9th cleaning run was found to be 86% of the initial flux for $\Omega = 10.47$ rad s$^{-1}$, whereas the same was 92% for $\Omega = 41.9$ rad s$^{-1}$. This is pretty obvious as for the first case all the cleaning runs were conducted at 10.47 rad s$^{-1}$, whereas for the second it was operated at 41.9 rad s$^{-1}$. As a result the local vacuum ($= \frac{1}{2} \rho V_o^2$ and $V_o \propto \Omega$) created on the membrane surface during cleaning run of the second case was nearly 15 times higher than that in the first leading
Design and performance characterization of a new shear enhanced module with inbuilt cleaning arrangement
to a higher disengagement rate as well as a higher disengaged amount of the rejected solute deposited on the membrane surface during the normal runs.

Figure 4.8. Variation of regenerated permeate flux (as obtained after each cleaning runs) with the cleaning run number for normal runs conducted at different rotational speed (\( \Omega \))

4.2.5. Variation of the ‘observed rejection’

Variation of the observed rejection \( (R_{obs}) \), defined as \( R_{obs} = 1 - \frac{C_p}{C_0} \) under steady state, i.e. at the end of first normal run with TMP at different rotational speed is shown in Fig. 4.9. The figure indicates an increasing trend of \( R_{obs} \) with TMP. This can be explained in terms of increased convective flow towards the membrane leading to a higher rejection at higher TMP. Further, the rejected solute forms an additional mass transfer resistance, which acts like a secondary membrane in series with the actual membrane. This phenomenon promotes higher rejection at increased TMP because high TMP not only increases the convective flux but also induces higher compaction of the deposited layer and thereby increases the rejection. A closer investigation reveals that the rate of change of observed rejection with respect to the applied TMP was much higher on the higher side values of rotational speed (\( R_{obs} \) was observed to increase by 19% for the change of TMP from 98.0 kPa to 588.4 kPa at \( \Omega = 41.9 \text{ rad s}^{-1} \), where as for the same change
of TMP, the change of $R_{obs}$ was only 9.5% at $\Omega = 10.47$ rad s$^{-1}$). The trend can be explained in terms of the nature of variation of $R_{obs}$ with respect to $\Omega$, as depicted in the inset of the same figure (Fig. 4.9).

![Figure 4.9. Variation of steady state observed rejection ($R_{obs}$) with TMP at different rotational speed ($\Omega$) (insert showing the same variation with ($\Omega$) at different TMP)](image)

High speed basket rotation was found to reduce $R_{obs}$, which could be attributed to a reduced concentration-polarization layer thickness at higher $\Omega$. This phenomenon establishes the shear enhancing character of the SBM module and clearly points out that the effective shear rate, which is responsible for scraping off the rejected solute from the membrane surface increases monotonically with the rotational speed of the basket. It is also to be noted that the rotation effect was much pronounced in differentiating $R_{obs}$ at different $\Omega$ on the lower side values of the applied TMP. However, with the increase of TMP, the relative difference of $R_{obs}$ was observed to decrease because the TMP has a more direct influence on the concentration-polarization layer thickness and on the secondary mass transfer resistance, thus on $R_{obs}$ than $\Omega$. Though not separately studied but the observed rejection is supposed to increase with the feed
Design and performance characterization of a new shear enhanced module with inbuilt cleaning arrangement

concentration as the deposited solute layer will be more compact and dense at higher feed concentrations.

4.2.6. Energetic considerations

It is necessary to investigate whether the increase in permeate flux induced by higher TMP and \( \Omega \) is not obtained at the expense of prohibitive energy cost. In the present study, the total electrical power consumed by the lab scale SBM module, which is a sum of power supplied to the feed pump and to the induction motor was measured with a wattmeter. The variation of power consumption with rotational speed at different TMP is shown in Fig. 4.10. In order to be more informative variation of the same with TMP at different \( \Omega \) has been also depicted as an inset to Fig. 4.10.

![Figure 4.10. Variation of average power consumption rate (\( \dot{E} \)) with rotational speed (\( \Omega \)) at different TMP (insert showing the same variation with TMP at different \( \Omega \)).](image)

The figures clearly indicate a linear variation of average power consumption both with TMP and \( \Omega \). As expected, the module was observed to consume maximum energy (\( \approx 0.94 \text{ kW} \)) when it was operated at highest TMP (\( =588.4 \)) and \( \Omega =41.9 \text{ rad s}^{-1} \). It is well known that for an induction motor the power consumption is proportional to the rotational speed. So for the present case \( \dot{E}_{\text{motor}} = k \Omega \), where \( k \) is a constant. On the other hand, for a triplex piston pump the
Design and performance characterization of a new shear enhanced module with inbuilt cleaning arrangement

power requirement ($\dot{E}_{\text{pump}}$) can be expressed as $\dot{E}_{\text{pump}} = \frac{gQ \times \text{TMP}}{\eta}$, where $\eta$ is the pump efficiency and $Q$ is the feed flow rate. Accordingly, the total power requirement becomes

$$\dot{E} = \dot{E}_{\text{motor}} + \dot{E}_{\text{pump}} = k\Omega + \frac{gQ \times \text{TMP}}{\eta}$$

(4.1)

From eqn. 4.1 it becomes evident that power varies linearly with both TMP and $\Omega$ provided $\eta$ and $Q$ remain unchanged. For the present study as mentioned earlier the retentate flow rate was fixed at $10^4$ m$^3$/s, where as the maximum permeate flow rate was $8 \times 10^7$ m$^3$/s, which is negligible in comparison to the retentate flow. So the feed flow rate ($Q$) may be considered to remain unchanged for all the experimental runs. Accordingly, as per eqn. 1 the power consumption rate becomes linear with respect to both TMP and $\Omega$, consistent with the trend depicted in Fig. 4.10.

Shear enhanced modules, in general consume higher energy compared to their cross flow counterpart. Primarily for this particular limitation shear enhanced module is still not widely accepted as it was expected to be. So for any newly proposed shear enhanced module energy cost should be considered seriously. The power uptake characteristic of the proposed module has been compared with the reported usage rate of other exiting shear enhanced modules as displayed in Table 4.1. The table clearly establishes the proposed module to be the most energy efficient as it is capable of producing the highest permeate flux at the cost of lowest energy consumption rate. Though it may seem that the Rotating disk dynamic filtration device as reported by Brou et. al. (Brou et. al., 2002) consumes less energy (=0.63 kW) than the proposed module (=0.94 kW) but it is to be noted that the reported energy value is the net energy, which was defined as the difference of total energy necessary in a filtration test and the energy required to drive the system without fluid.

4.2.7. Performance comparison with other modules

Exhaustive literature survey revealed that most of the membrane filtration studies using the same feed solution (PEG/water) were mostly limited to cross flow modules. The scope of dynamic shear enhanced modules for the present solute-membrane combination has not been
Design and performance characterization of a new shear enhanced module with inbuilt cleaning arrangement

explored at all. Accordingly, for the purpose of comparison, two well known shear enhanced modules, namely (i) Single Stirred (SS) and (ii) Rotating Disk Membrane (RDM) were chosen and filtration experiments were performed under identical parametric conditions as that of the SBM module. It is to be noted that both the SS and the RDM are shear enhanced dead end modules. In a standard SS module a high speed stirrer was placed in the close vicinity of a stationary membrane to promote disengagement of the solutes and subsequently to increase the permeate flux.

<table>
<thead>
<tr>
<th>Module</th>
<th>Membrane/ feed combination</th>
<th>Steady permeate Flux (L m$^{-2}$ hr$^{-1}$)</th>
<th>Motor speed (rpm)</th>
<th>Maximum power consumption (kW)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotating disk membrane (RDM)</td>
<td>NF membrane / diluted skim milk (1:2)</td>
<td>400</td>
<td>2500</td>
<td>1.3 (total power)</td>
<td>Luo et. al., 2010</td>
</tr>
<tr>
<td>Rotating disk dynamic filtration</td>
<td>Nylon membrane (pore size 0.2 μm)/ baker yeast suspension</td>
<td>200</td>
<td>2000</td>
<td>0.63* (net total power)</td>
<td>Brou et. al., 2002</td>
</tr>
<tr>
<td>Vibratory Shear Enhanced Process</td>
<td>Desal AG RO membrane/ skim milk</td>
<td>180</td>
<td>2000</td>
<td>18.15 (total power)</td>
<td>Frappart et. al., 2008</td>
</tr>
<tr>
<td>Vibratory Shear Enhanced Process</td>
<td>Ceramic membrane (plane, MWCO 150 kDa)/ Low heat skim milk</td>
<td>40</td>
<td>2000</td>
<td>36.9 (total power)</td>
<td>Grangeon and Lescoche, 2000</td>
</tr>
<tr>
<td>Spinning basket membrane (SBM)</td>
<td>Polyethersulfone (PES) membrane (MWCO 5 kDa)/ PEG 6000/ water</td>
<td>411</td>
<td>400</td>
<td>0.94 (total power)</td>
<td>Present study</td>
</tr>
</tbody>
</table>

Table 4.1. Comparison of the proposed SBM module with the reported shear enhanced membrane modules in terms of power consumption.
Design and performance characterization of a new shear enhanced module with inbuilt cleaning arrangement

As the solute back transport from the membrane surface was accomplished by a single stirrer the module has been named as “Single Stirred”. The polarization effect could be further reduced in a RDM module where the membrane was also subjected to rotation, necessarily in the opposite direction with respect to a closely placed stirrer. Accordingly, the permeate flux obtained from a RDM module was expected to be higher than a SS module operating under similar operating conditions. In this comparative study, it was assumed that the stirrer speeds of the SS and RDM modules were equivalent to the basket rotational speed of the proposed module. The RDM module was operated at its highest possible membrane speed of 62.5 rad s\(^{-1}\) in order to obtain maximum permeate flux at a constant stirrer speed.

The effects of TMP at fixed \(\Omega\) and \(C_0\), on the steady permeate flux (same as the flux obtained at the end of 2 h continuous run) for all the three different modules, namely the SS, RDM and the SBM is shown in Fig. 4.11. For different TMP, it can be clearly observed from the figure that the steady permeate flux of the proposed module was 58-67% higher than that of RDM, whereas in comparison to SS module it was 250-380% enhanced.

![Figure 4.11. Steady permeate flux (as obtained at the end of first normal run) at different TMP for (i) Single stirred (ii) RDM (membrane speed= 62.5 rad s\(^{-1}\)) and (iii) SBM module](image)

The flux enhancement of the present module might be attributed due to different velocity fields prevalent in the different modules. In the proposed SBM module the large tangential
Design and performance characterization of a new shear enhanced module with inbuilt cleaning arrangement

component (with respect to the membrane surface) of the velocity vector was responsible for disengaging the solutes. In case of SS and RDM modules, because of their dead-end feature, the axial velocity component was primarily responsible for similar action. In general, a tangential momentum flux more effective than its axial counterpart in scraping a surface was present in the proposed SBM module, and hence the permeate flux was enhanced in the SBM module compared to its SS or RDM counterpart.

The similar trend was being maintained in the variation of steady permeate flux with \( \Omega \) but at fixed TMP and \( C_0 \) as shown in Fig. 4.12. Here for the mentioned range of \( \Omega \) the steady flux of the SBM module was 45-95% higher than its RDM counterpart, where in comparison to SS it was 300-450% enhanced.

![Figure 4.12](image)

**Figure 4.12.** Steady permeate flux (as obtained at the end of first normal run) at different \( \Omega \) for (i) Single stirred (ii) RDM (membrane speed= 62.5 rad s\(^{-1}\)) and (iii) SBM module

In relation to that it is also to be noted that for all the experimental runs the RDM was subjected to operate at its highest possible membrane speed i.e. at 62.5 rad s\(^{-1}\). A legion of studies on cross flow modules for the same feed solution was reported. The performances of some of them are reviewed here in comparison to the proposed SBM module and are presented in Table 4.2.

It can be seen from the table that the highest permeate flux reported was 144 L m\(^{-2}\) hr\(^{-1}\) at a TMP of 170 kPa (Sulaiman et. al., 2001), where in the present module even at 98 kPa the flux was 194
Design and performance characterization of a new shear enhanced module with inbuilt cleaning arrangement

It is also to be noted that the feed concentration in the present study (=20 kg m\(^{-3}\)) was nearly six fold higher than the same of the reported investigation (=3.2 kg m\(^{-3}\)). From the experimental evidences, it becomes clear that the proposed SBM module is much superior in terms of permeate flux than the other cross-flow units and shear enhanced modules with similar characteristics. Additionally, for the flux recovery, all the existing membrane filtration units would require either chemical cleaning or periodic back washing or similar methods. In the proposed module, the flux recovery was achieved by an inbuilt mechanism and membrane cleaning was accomplished without the frequent use of cleaning agents or washing liquid. From the foregoing discussion, it is clear that the proposed SBM module can perform efficiently than the existing cross-flow units.

<table>
<thead>
<tr>
<th>Module</th>
<th>Membrane specification</th>
<th>Bulk concentration of PEG (kg/ m(^3))</th>
<th>TMP (kPa)</th>
<th>Steady permeate flux (L m(^{-2}) hr(^{-1}))</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross flow UF</td>
<td>Monotubular ceramic membrane (MWCO: 15 kDa)</td>
<td>5 (PEG-35000 Da)</td>
<td>400</td>
<td>80</td>
<td>Vela et. al., 2009</td>
</tr>
<tr>
<td>Tubular cross flow UF</td>
<td>Polyethersulfone membrane (MWCO: 9 kDa)</td>
<td>3.2 (PEG-20000 Da)</td>
<td>170</td>
<td>144</td>
<td>Sulaiman et al., 2001</td>
</tr>
<tr>
<td>Cross flow UF</td>
<td>Tubular ceramic membrane (MWCO: 15 kDa)</td>
<td>5 (PEG-35000 Da)</td>
<td>400</td>
<td>50</td>
<td>Vela et. al., 2006</td>
</tr>
<tr>
<td>Cross flow UF</td>
<td>TiO(_2)-Al(_2)O(_3) monotubular membrane (MWCO: 5 kDa)</td>
<td>5 (PEG-35000 Da)</td>
<td>500</td>
<td>60</td>
<td>Vela et. al., 2007</td>
</tr>
<tr>
<td>SBM</td>
<td>Polyethersulfone membrane (MWCO: 5 kDa)</td>
<td>20 (PEG-6000 Da)</td>
<td>98</td>
<td>194</td>
<td>present study</td>
</tr>
</tbody>
</table>

**Table 4.2.** Comparison of the proposed SBM module with the reported cross flow units in terms of permeate flux.
4.3. Conclusion

A completely new shear enhanced membrane module with an inbuilt cleaning facility has been proposed in the present study. Considering its inherent structural similarity with well known Spinning Basket Reactor the module was named as Spinning Basket Membrane (SBM) module. Regarding the cleaning performance, it may be stated that for PEG 6000/ water treated by PES membrane of 5 kDa MWCO the average regenerated flux was found to be more than 95% of the initial flux, where the steady state flux was within 65-75% of its initial counterpart. Moreover, after each normal run of 2 h duration the cleaning run was conducted only for 300 s. Even for every continuous experimental run of 21 h duration (consists of 10 normal runs intervened by 9 cleaning runs) the final regenerated flux was within 85-95% of the flux at the time of start up.

On the other hand, the module also functioned well as a shear enhanced device. This was reflected by low values of flux drop from initial to the corresponding steady state condition under different transmembrane pressure, feed concentration and rotational speed. This was due to vigorous circulation flow created by basket rotation, which limits the phenomenon of solute built up at the membrane surface. For a better understanding, the power uptake rates under different $\Omega, C_0$ and TMP has been also included in the present work.

Considering the novelty of the system developed it was concluded that this module, presently in lab scale, could be scaled up for continuous industrial operation as it can curtail the number of necessary chemical cleaning to a large extent leading to an uninterrupted production of the corresponding unit. It would be interesting to explain the behavioral features of the proposed module from the perspective of computational fluid dynamics (CFD).