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Effects of manual interventions in the winding process on the performance of spiral wound membrane module

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ABSTRACT

Thin-film composite desalination membranes of pressure-assisted membrane-based separation processes are predominantly used in spiral-wound membrane (SWM) module configuration. The winding process to convert the flat sheet membranes into SWM modules using spacers and adhesive application can be manual, semi-automatic, or automatic. The commercially available modules are wound with an automatic/semi-automatic process, which eliminates human errors and results in the consistent performance of the membrane modules, given that the membrane-making process is also consistent. However, a semi-automatic or manual winding process involves manual handling of the membrane, which may deteriorate its performance. In this article, we have examined the effects of human interventions during semi-automatic winding on the performance of the module and membrane coupons taken from the dissected module. It was observed that the mechanical damages observed on the membrane surface and the inconsistent width of the adhesive lines are the root causes of inferior performance (in terms of salt rejection and permeate flux) of some of the SWM modules than the pristine membrane coupons.

Keywords: Desalination; Spiral wound membrane module; Membrane winding

1. Introduction

With the increasing population and standards of living, the need for freshwater is growing day by day. Since the natural reservoirs of potable water are limited, it is essential to consider ways to convert saline water or wastewater into potable water. However, the conversion processes, especially those involving phase change or elevated temperature operations, need energy and thus generate a carbon footprint. Membrane-based separation processes are less energy-intensive and are widely used in various industries for desalination, water clarification, wastewater treatment, the concentration of fruit juices and dairy products, etc. [1,2]. The state-of-the-art polyamide separation layer of the thin-film composite (TFC) desalination membrane is fabricated by interfacial polymerization on flat sheet support made via phase inversion [3].

The commercial separation membranes are available in spiral wound, hollow fiber, tubular and plate and frame configurations [4]. Amongst these, hollow fiber module configuration is often used for ultrafiltration. In contrast, spiral wound configuration is well known for flat sheet ultrafiltration and thin-film composite membranes. The inherent advantages of spiral wound design include high packing density [5], better flow mixing, simple construction [6], and ease of operation.

The spiral-wound membrane (SWM) module configuration for separation membranes was first proposed in 1965

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by Michaels [6]. The design consisted of only one base strip material instead of separate feed and permeate spacers. Further, the feed stream intake to the module was through a central perforated pipe, and the concentrate stream was discharged through a nipple in the bottom center of the pressure vessel. However, adequate mixing of the feed flow was not considered in the design. The SWM design eventually evolved with time [7–23], and the widely adopted current design was proposed in the late 1970s [17], which uses multiple membrane leaves of optimum length and the feed spacers for adequate flow mixing to avoid concentration polarization and alleviate fouling concerns.

High salt retaining capacity is very important for a membrane module to achieve low specific energy consumption in the separation processes [24]. If the salt rejection is lesser than required, an additional number of stages will be needed to achieve a required permeate quality, leading to higher specific energy consumption [25]. The structural uniformity of the delicate thin separation layer across the TFC membrane area is necessary to achieve the required solute rejection. Even a uniformly fabricated membrane may have compromised solute rejection if the winding process involves manual interventions. Furthermore, the active (permeable) area of the membrane in the SWM module has to be maximized to achieve higher flux and hence higher recovery per membrane module at the same operating pressure. Maximizing the recovery per membrane module will reduce the required number of modules and, thus, the capital cost. It is necessary to optimize the width and location of the adhesive lines to increase the active area of the membrane. If the width is excessive or the adhesive lines are located far from the edges, the active area will be reduced. Additionally, the amount of adhesive applied on the membrane and its viscosity will determine the final width and thickness of the adhesive lines. However, if the adhesive lines are located too close to the edges, the adhesive lines may get removed when the module is trimmed at both the ends for achieving the required length, causing leakage of feed into the permeate. Therefore, identification of optimized location and width of adhesive lines are essential. Notably, the location and width of adhesive lines and the salt retaining capacity of the membrane in commercial SWM modules are uniform because of the automated module winding process. The manual and semi-automatic module winding processes may enhance the inconsistency in the above factors causing inferior performance of the SWM module.

In this article, we have studied the effect of manual intervention in the semi-automatic winding process of SWM modules on the width and location of adhesive lines and various mechanical damages that may occur on the membrane surface.

2. Experimental section

2.1. Materials

HB Fuller UR3501 A and B, a two-component adhesive, was received from HB Fuller, USA. It was used in the A:B composition of 100:62.5 (as prescribed by the manufacturer) to seal the permeate stream. Fevitite HN-111 + SS-111 was procured from Pidilite, India. It was used in the HN:SS composition of 1:1 to hard coat the 4040 SWM modules. Polypropylene feed spacer of 31 mils and polyester permeate spacer of 275 microns thickness were used in feed channel and permeate channel, respectively. NaCl (Fisher Scientific, 99.9% pure) was used for the preparation of synthetic feed solution.

2.2. Preparation of TFC membrane

The flat sheet TFC membrane for brackish water desalination was prepared on polysulfone support as per the protocol mentioned in the earlier publications [26,27].

2.3. Preparation of 4040 SWM modules

SWM modules of 4-inch diameter and 40 inch overall length (commercial code: 4040) were prepared. Envelopes were prepared with permeate spacer sheets, and they were ultrasonically spot welded to the perforated PVC central tubes. In each SWM module, 04 nos. of membrane sheets of length ~2.3 m each and feed spacer of the same length were inserted inside the envelope and spirally wound around the central tube semi-automatically with manual application of winding pressure for requisite tightness of the membrane assembly. After the completion of the winding, pneumatic pressure was applied from the bottom of the wound assembly, and adhesive tape was manually applied on the curved surface to affix its diameter. The rolled assembly was left for 24 h at room temperature to cure the adhesive lines, and subsequently, it was trimmed from both ends to achieve its desired membrane length of 36 inch. Perforated plastic end caps were installed on both ends, installing a rubber seal on one end. Finally, a hard coating was applied on the outer surface, and it was stored at a curing temperature of 70°C ± 5°C for 4 h.

2.4. Testing of membrane coupons and 4040 SWM modules

The preliminary quality testing of the pristine TFC membrane was performed by cutting it into several rectangular coupons (35 nos.) of size 113 × 57 mm^2. The coupons were tested to measure the salt rejection at an operating pressure of 250 psi and crossflow rate of 200 LPH, which corresponds to a crossflow velocity of 0.61 m/s (approx.) on the membrane surface at 25°C ± 1°C. Four crossflow cells (Sterlitech CF042 with active membrane area 42 cm^2 [28]) were used in series for testing the membrane coupons. The membrane coupons were stabilized with the saline feed at 350 psi pressure and 200 LPH flow rate for 1 h to achieve a steady-state. A solution of 2,000 mg/L NaCl was used as feed.

The salt rejection and permeate water flux of the 4040 SWM modules were measured under a crossflow rate of 1 m^3/h, which corresponds to the crossflow velocity of 0.076 m/s on the membrane surface, at 250 psi operating pressure and 25 ± 2°C temperature. The modules were stabilized with the saline feed at 350 psi pressure for 1 h to achieve a steady-state. A solution of 2,500 mg/L NaCl was used as feed.

A 4040 SWM module was randomly chosen for the purpose of autopsy. It was cut into pieces, and the membrane was visually observed for damages. Multiple coupons of size 113 × 57 mm^2 (20 nos.) were cut from all the membrane leaves of the SWM module and tested for salt rejection at an operating pressure of 250 psi and crossflow rate of 200 LPH. The membrane coupons were stabilized with the saline feed at 350 psi pressure and 200 LPH flow rate for 1 h to achieve a steady-state. A solution of 2,000 mg/L NaCl was used as feed.

3. Results and discussion

The 4040 SWM modules were semi-automatically fabricated using a brackish water reverse osmosis (BWRO) membrane. The membrane was fabricated by interfacial polymerization on the polysulfone support obtained by the phase inversion process [26,27].

In addition to membrane leaves, the process of making an SWM module involves the use of various other components viz. feed spacer, permeate spacer, product tube, adhesive, etc., out of which the feed spacer touches the active surface of the membrane (Fig. 1). Winding pressure is needed to roll the membrane assembly into the required diameter. If excessive winding pressure is applied, it can result in an indentation of the feed spacer on the membrane surface [29]. In addition, if there is any rubbing between feed spacer and membrane surface, the abrasion on the membrane surface is most likely. The probability of abrasion is higher with the manual interventions in the winding process. These damages may deteriorate the overall performance. The damage of the polyamide layer will cause higher local permeate flux compared to the remaining membrane area and may act as a nucleation point for fouling.

A total of 22 nos. of 4040 SWM modules were fabricated in a batch and tested. The results are summarized in Table 1. The salt rejection and permeate flux of the best performing membrane module were 97.98% and 288 LPH, respectively, at 250 psi operating pressure. The average salt rejection and permeate flux of the module batch were 92.8% ± 5.6% and 289.2 ± 57.1 LPH, respectively. The standard deviations on both the readings are very high, exemplifying the inconsistency in the performance of the prepared SWM modules.

A module was randomly selected and dissected to investigate the reasons for the inferior performance of some of the modules. The two primary root causes were noticed:

- Mechanical damage (e.g., indentation, delamination, abrasion, scratch, etc.) on the membrane surface causing inferior salt rejection.
- The inconsistent thickness of the adhesive lines causing reduced effective membrane area and hence, the permeate flux.

The mechanical damages (Fig. 3) occurred mainly due to the manual handling of the membrane during the winding process. However, the membrane-making process – (i) phase inversion to prepare the support layer and (ii) interfacial polymerization to prepare the thin separating layer, can also contribute to these damages. If the support layer is too thick (Fig. 3a), the salt rejection of the pristine membrane coupon may not be significantly low; however, the chances of delamination (Fig. 3b) during winding will increase, which may cause inferior salt rejection. As observed from Fig. 2, the inconsistency in the salt rejection data of the delaminated membrane coupons is the major factor. In addition, the membrane has to be folded to make a leaf for winding around the central perforated tube. Hence, it was suspected that the thin film on the fold line might be damaged, leading to a lower salt rejection in the module. However, as evident from Fig. 2, the mean salt rejection of membrane coupons selected from the membrane

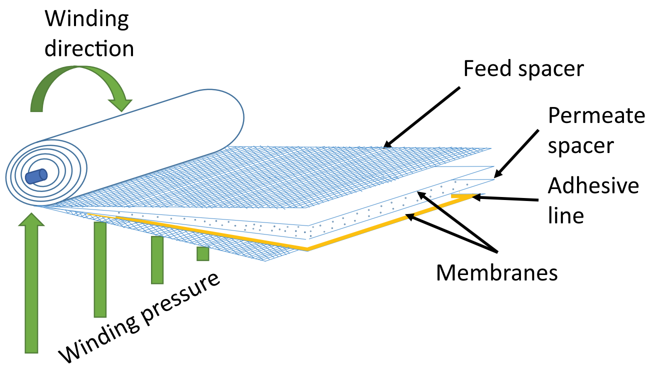

Fig. 1. Schematic diagram of an open SWM module and the process of winding it.

Table 1
Testing data of membrane modules at 250 psi, 2,500 mg/L feed, and recovery in the range of 8%–22%

Module nomenclature	Salt rejection (%)	Flux (LPH)*	Flux (LMH)**
4040/1	88.6	411	67.4
4040/2	76.3	471	77.2
4040/3	89	276	45.2
4040/4	96	262.8	43.1
4040/5	96.4	280.8	46.0
4040/6	95.14	288	47.2
4040/7	96.48	284.4	46.6
4040/8	95.68	255.6	41.9
4040/9	96.96	237.6	39.0
4040/10	96.23	259.2	42.5
4040/11	94.2	270	44.3
4040/12	94.56	280.8	46.0
4040/13	96.78	223.2	36.6
4040/14	92.74	280.8	46.0
4040/15	90.3	208.8	34.2
4040/16	89.6	291.6	47.8
4040/17	82.6	316.8	51.9
4040/18	85	306	50.2
4040/19	94.8	256.8	42.1
4040/20	97.86	285.6	46.8
4040/21	97.98	288	47.2
4040/22	97.59	328.8	53.9

*LPH: Litres per hour;
**LMH: Litres per square meter per hour (considering a constant membrane area of 6.1 m^2 for SWM module).

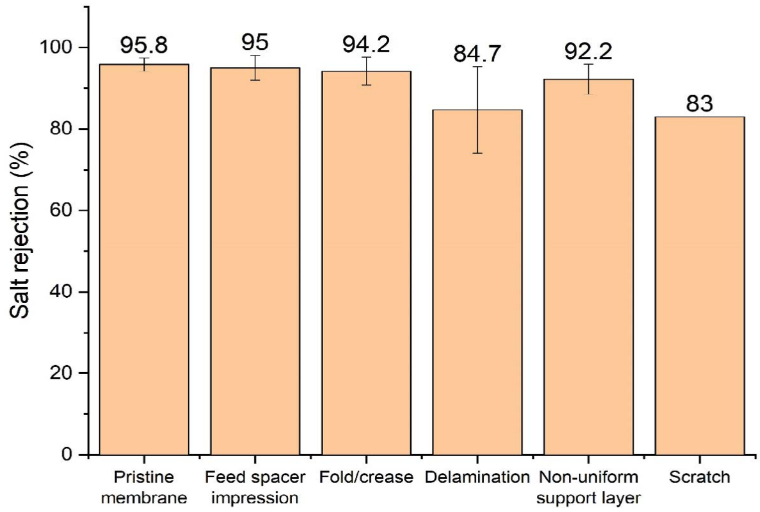

Fig. 2. Bar chart depicting the coupon level data of salt rejection of pristine membrane and the membranes damaged by manual intervention in the module winding process.

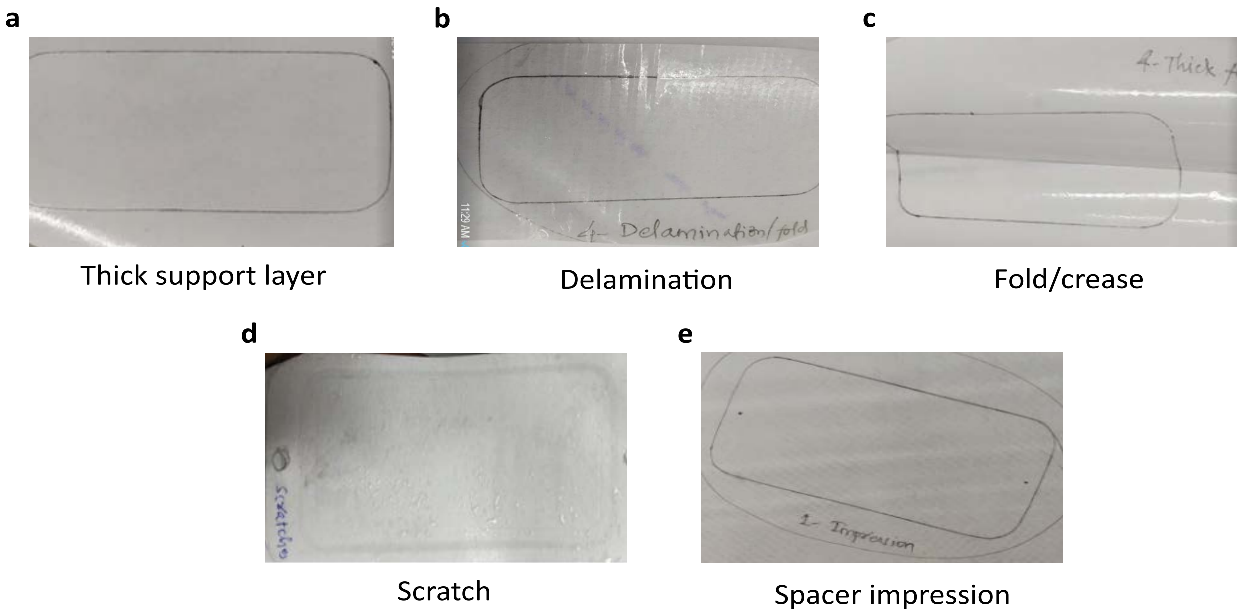

Fig. 3. Photographs of the membrane surfaces showing the damages that occurred due to the manual intervention in the module winding process.

area with fold lines (Fig. 3c) is within an acceptable range (the change in salt rejection is statistically insignificant). A location with scratch was identified in the dissected membrane module (Fig. 3d), which shows that the manual operation may have resulted in rubbing of a sharp object (e.g., edge of the feed spacer sheet while inserting it inside the membrane leaf) on the membrane surface. As expected, the salt rejection of the membrane coupon selected from the membrane area with scratch went down to 83%.

Spacer indentation is usually observed in many commercial SWM modules, as found in our case. However, the salt rejection data of the membrane coupons selected from the membrane area with feed spacer impression (indentation) (Fig. 3e) suggest that its effect on the salt rejection is not statistically significant (Fig. 2). To realize the sub-micron scale damage to the thin polyamide layer due to the spacer impression, a pristine membrane was pressurized (2.5 kg/cm^2) with a feed spacer on top, and scanning electron microscope (SEM) images were taken. The impression of the spacer on the membrane surface was observed, as shown in Fig. 4. However, the higher magnification SEM image confirms the integrity of the thin polyamide layer. Hence, it is confirmed that the impression has little or no effect on the module's performance.

As observed from Table 1, the SWM modules having salt rejection of more than 96% (which can safely be assumed defect-free), the permeate flux varies from 237.6 to 328.8 LPH. The inconsistent permeate flux may have arisen

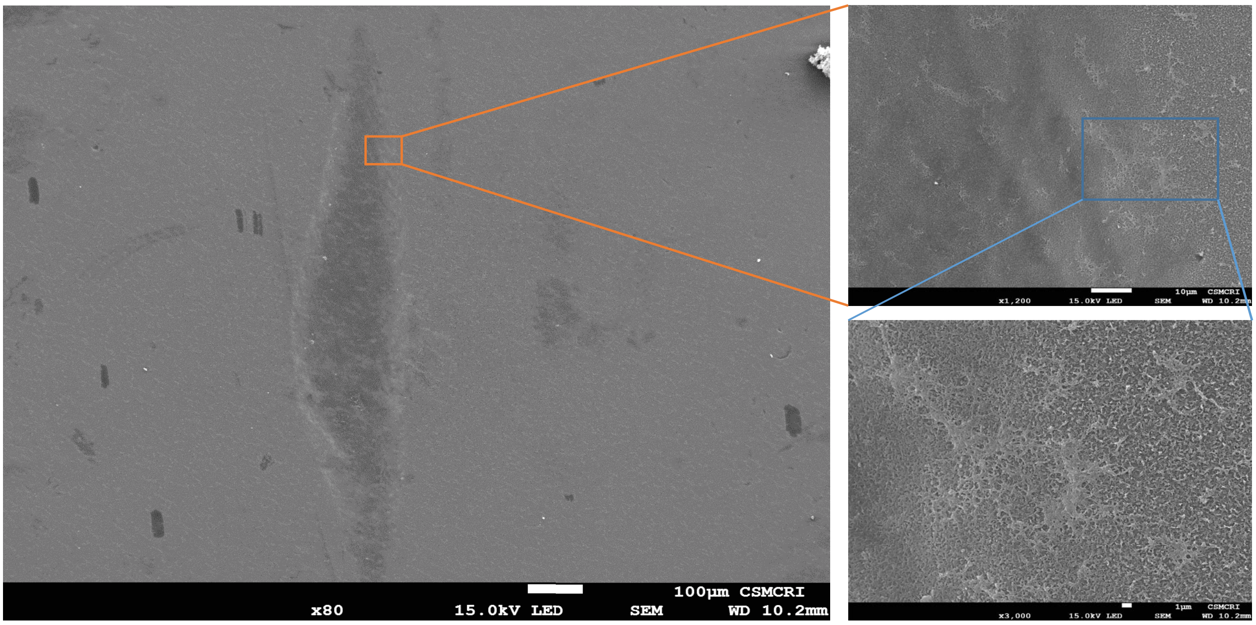

Fig. 4. Scanning electron microscope images of an impression of feed spacer on the membrane surface, obtained by intentionally applying a pressure of 2.5 kg/cm^2 on the feed spacer. The high magnification image confirms that the feed spacer impression does not cause any damage to the thin polyamide layer.

Fig. 5. Adhesive lines as observed when the module was reopened for observation after applying winding pressure. Application of the winding pressure ensures that the adhesive has spread in the free space.

due to uncontrolled application (flow rate of adhesive application and location) of the adhesive lines and hence its thickness. The excessive width of adhesive lines resulted from the high flow rate of adhesive and subsequent application of winding pressure reduces the membrane's active surface area, leading to a lower permeate water flux (Fig. 5).

As described in Table 2, the well-accepted width of adhesive lines is 4 cm, and the lesser width poses chances of cutting the whole adhesive lines while trimming the module from both sides. However, in the case of manual adhesive application, the flow rate of adhesive application is uncertain and differs from module to module. The consequences of the manual adhesive application are higher adhesive consumption and reduction in active membrane area (Table 3).

Table 2
Width of the adhesive line in the fabricated SWM module and well-accepted limit

4040 module	Width of adhesive lines (cm)	Shortcoming
Well accepted [30]	4	–
Fabricated SWM module	8–12	~2–3 times adhesive consumption and reduced active area

Table 3
Comparison of active surface area in commercial 4040 SWM module and the fabricated SWM module

Trade name	Active area (m^2)	Shortcoming
FilmTec™ LE-4040 [31]	7.2	–
Fabricated SWM module	6.1 (approximate)	~15.3 % reduction in the active area as compared to the commercial module

4. Conclusion

Uniform and steady winding pressure is essential for the consistent performance of SWM modules in terms of salt rejection and permeate water flux. Manual application of winding pressure can lead to the requirement of subsequent tightening of the windings, leading to rubbing of the membrane and feed spacer. The rubbing will lead to mechanical damages of the membrane, such as abrasion, delamination, scratches, etc. Besides this, the manual adhesive application results in the inconsistency in the active surface area of the membrane in the module, affecting permeate water flux. We conclude that a fully automatic winding set up with an automatic adhesive applicator is necessary for efficient winding of SWM modules, which the commercial membrane manufacturers may have been using.

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