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Applications of Helical Versus Straight Hollow Fiber Membranes: A Review

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HIGHLIGHTS

- A comprehensive comparison was performed between helical and straight hollow fibers.
- Applications of helical hollow fibers membrane were studied.
- The use of helical fibers minimizes fouling and concentration polarization.
- Helical configuration promotes turbulence.

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ABSTRACT

The production of straight and helical hollow fibers plays an important role in developing hollow fiber membrane technology that encompasses a broad range of designs. During the last two decades, scientific studies devoted to straight hollow fibers were more abundant than those focused on helical fibers. Several major applications considering side-by-side testing of these two geometries are discussed in this review. For membrane extraction, desalination, and membrane contactor processes, it is observed that permeability rates are 10%-400 % higher for helical fibers compared to straight fibers. This outcome is justified by the presence of Dean-vortices-induced flow turbulences inherent to the geometry of helical membranes. These conditions give rise to an uptake of mass and heat transfer coefficients and a reduction of temperature and concentration polarization phenomena. Aside from enhanced flow properties, helical hollow fiber bundles tend to be more robust by design, thus exhibiting better resiliency over long service operations than straight bundles. One persistent shortcoming of the helical fibers seems to be an increase in pressure drop. However, this does not always translate into a higher energy consumption – i.e., versus straight bundles. Given the performance advantage, product robustness, and adaptiveness to a broad range of applications, the adoption of helical hollow fiber technology deserves growing support from the membrane community in academic and industrial settings.

1. Introduction

The field of separation sciences has gained increased visibility throughout the years. In particular, the number of articles dedicated to membrane distillation studies has steadily expanded between 2000 and 2021, as depicted in Figure 1 (a). It can be noticed that the publication rate follows two distinct regimes (slopes) during these two decades displaying a slow progression during the 2000-2009 period and followed by a sharp uptake in pace after 2010. More specifically, researchers have sought to leverage hydrodynamic phenomena' simulation and modeling studies to optimize membrane distillation operating parameters [1–5]. Furthermore, the choice of membrane materials and fabrication processes have been widely explored to increase the permeate flux and mitigate fouling phenomena [6–10]. According to Culfaz et al. [11], the helical configuration of the membrane promotes turbulence and therefore causes a significant reduction in concentration polarization. This reduction is attributed to Dean vortices, occurring at a flow rate above the critical Re. Indeed, under these conditions, a secondary flux can be created, and the depolarization of fouling can be established [11–13]. In terms of membrane fabrication, the fibers can be produced by spinning a polymeric solution that passes through a hollow cone spray nozzle. Fibers can be formed by precipitating the spun solution in a coagulation bath, followed by a controlled drying phase. Straight parallel fibers can be

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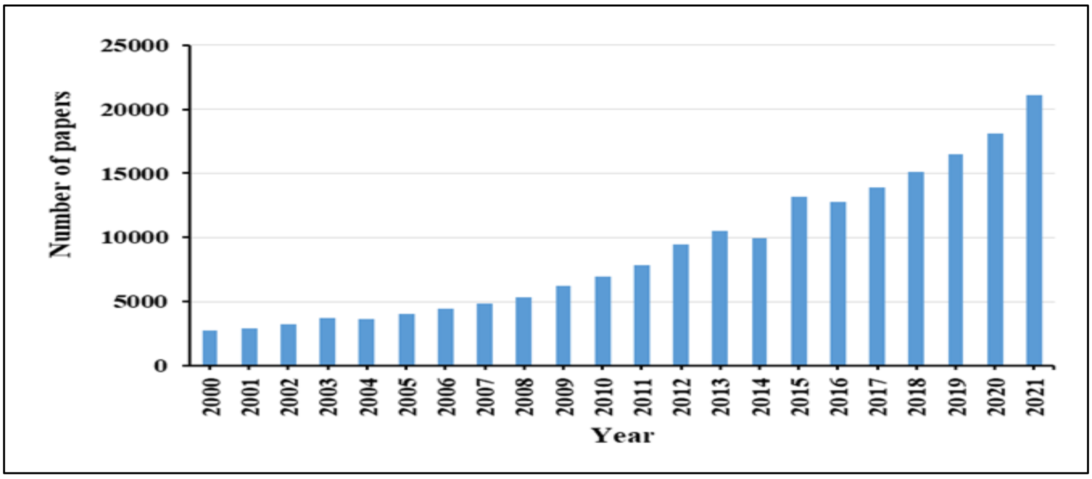
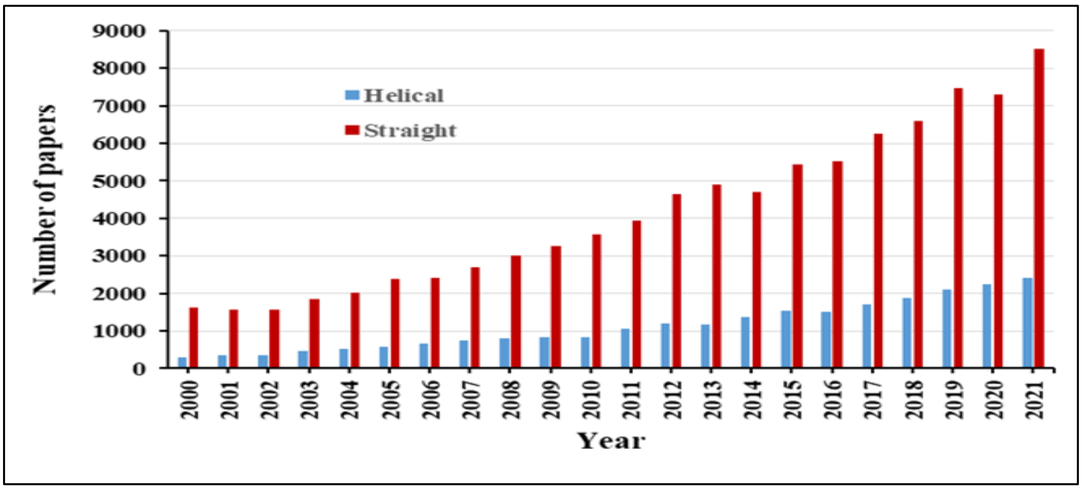
obtained by cutting and collecting them from the take-up drum of the spinning unit, then packing them in parallel orientation inside a module. Moreover, helically wound fibrous mats can be fabricated by spinning a continuous fiber from a rotating ring, then collecting it onto a core that travels back and forth inside the ring [14–16]. Although the capital cost differences between these two filter configurations are hardly discussed by technical experts, it does not seem to be a burden since the engineering designs are not drastically changed, and the fabrication steps are not too cumbersome.

Nowadays, a key area of interest lies in coupling carefully selected membrane distillation configurations with renewable energy sources to better compete against other distillation techniques [17–19]. Many membrane filter designs can be tested, including hollow fiber, planar, tubular, and spiral modules [20–22]. The demand for hollow fiber modules has constantly been rising because their advantageous area-to-volume ratio (relative to flat sheets) facilitates the optimization of process performance, and their low energy consumption contributes to a low operating cost [23,24]. Hence, hollow fibers can be used in different geometries, such as straight and helical hollow fibers [25–27]. According to Figure 1(b), the number of published papers discussing straight designs has been greater than that of helical fibers in the past two decades. Yet, the rate of helical hollow fibers publications outperformers that for straight hollow fibers by almost 150% during that same period.

Membrane distillation modules are generally made of fibers assembled in a straight form. Wirth et al. [28] conducted a side-by-side experimental study and tested straight and helical cartridges together. They established that the permeate flux of the helical module was almost 19% higher than that of the straight wound bundle. Indeed, the helical design was thought to enable the occurrence of a turbulent flow stream, which significantly enhances thermal transfer. Mallubhotla et al. [29] also compared these two configurations in a similar fashion, whereby the polymeric membrane was made of polyethersulfone fibers exhibiting an internal diameter of 270 µm and an external diameter of 620 µm. Furthermore, the helically wound hollow fibers had a pitch turn of 0.099 m. The experimentation presented in Figure 2 describes two modules tested under similar operating conditions. The obtained results indicated that the fiber configurations (helical or straight) and the pH of the feed solution did not affect the permeate flow. Moreover, these two designs exhibited comparable pressure drop values in charge circulation inside the fibers for a feed flow rate of 50 ml/min. However, when feed flow reaches a 200 ml/min threshold, the pressure drop caused by helical fibers is 2.4 times greater than that obtained for straight fibers Figure 3 [29].



(a)



(b)

Figure 1: Number of published articles between 2000 and 2021 (Google Scholar) (a) membrane distillation (b) straight and helical fiber

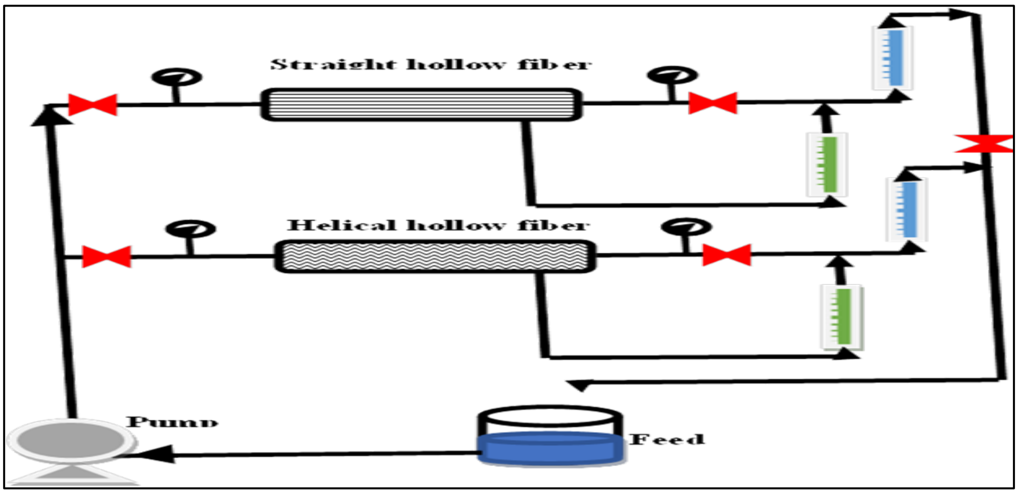


Figure 2: Experimental installation for testing of the helical and straight modules

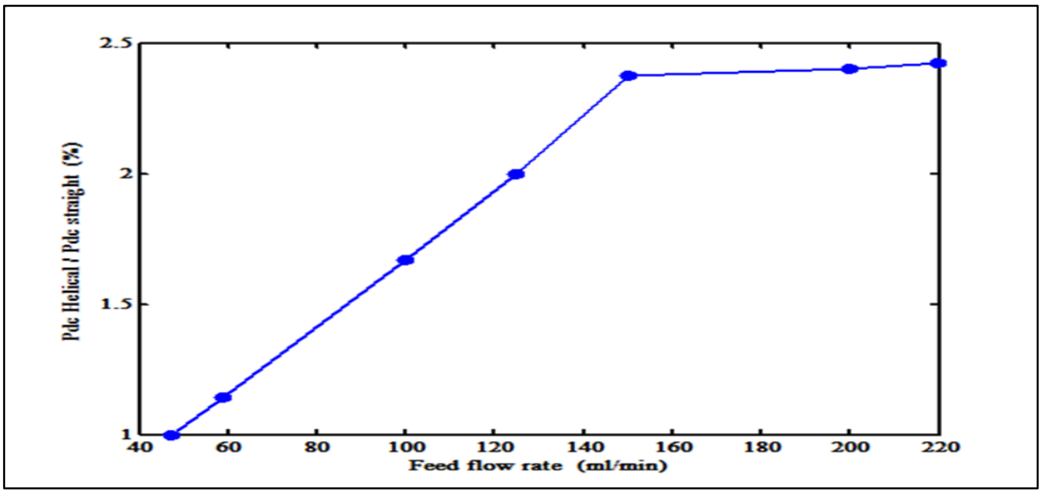


Figure 3: Evolution of the ratio between the helical and linear pressure drop as a function of the feed flow rate

2. Use Of Helical Hollow Fibers in Desalination

Helical hollow fibers were recently introduced in membrane desalination processes, as summarized in the following overview in Table 1.

A numerical study was conducted to analyze the difference in distillation efficiency between helical and straight hollow fibers for sweeping gas membrane distillation applications [30]. The upstream flow is reported to increase distillation efficiency (permeate flux) by 11%, with a decrease in the friction coefficient (pressure drop) by 28%. Additionally, distillation efficiency varied negatively with the increase of Reynolds number. Indeed, a rise in turbulence leads to higher heat transfer coefficient values, which translates to faster trans-membrane heat exchanges. A bench scale of direct contact membrane distillation set-up, presented by Teoh et al. [31], was tested to study the effects of baffles, spacers, and different fiber geometries on the permeate flux. According to this study, the heat transfer coefficient for the feed side increased from 2600 W/m^2K with the un-baffled module to 3750 W/m^2K in the presence of helical baffles, which reflects a flux gain of 28%. When hollow fibers exhibiting wavy geometries were tested, the flux enhancement reached nearly 40% without introducing any external turbulent promoter. This boost was explained by the fact that for the fibers with un-straight geometry, an increase of turbulence in the shell–side flow leads to a rise in mass transfer and permeate flux. In another study, Ali et al. [32] assessed the effect of wavy/helical/straight hollow fiber configurations on permeate flux and energy consumption for the case of direct contact membrane distillation and running with permeate flow of 100 ml/min at 20°C. They established that higher feed flows (fiber shell region) combined with helical and wavy modules would yield the highest permeate flux values. Such enhancement is related to thermal polarization improvements on both feed and permeates sides of the membrane. The progression of permeate flux for wavy and helical hollow fibers with Reynolds number was similar. However, when the value of Reynold numbers exceeded 1,500, the helical modules showed better energy efficiency than the straight designs. When these two configurations were used to concentrate whey, the concentrations were 13.7% and 18.6% for straight and helical hollow fibers, respectively. In terms of pressure drop, helically wound fibers exhibited the highest value but their energy pumping cost per unit flux was 17% lower that of straight fibers.

Table 1: Examples of applications leveraging helical hollow fibers for membrane distillation studies

Operating conditions	PE*	IPD**	Remarks	Ref.
Sweeping gas membrane distillation Seawater desalination Number of fibers in membrane module 2000-6000 Length of membrane module 0.348 m	29% above that of the straight hollow fiber	Increase of pressure drop by 400% versus that of straight hollow fiber	Simulation study Upstream flow has a great potential	[30]
Direct contact membrane distillation Hollow fiber in PP Length of hollow fiber membrane module: 0.15 m Fiber outer diameter: 370 µm Fiber inner diameter: 260 µm Membrane porosity: 35% Salinity of feed water: 3.5%	36% over that of the straight hollow fiber	Pressure drop increases without indicating values	Experimental study. Membrane module designed with spaces and baffles	[31]
Direct contact membrane distillation Hollow fiber in PP Fiber outer diameter: 2.70 mm Fiber inner diameter: 180 mm Membrane porosity 73% Permeate flow: 100 ml/min Permeate temperature: 20°C Whey solution (10%) for feed	47% over that of the straight hollow fiber	Values not indicated	Experimental study Energy efficiency for helical fibers is 64% higher than for straight fibers	[32]
Vacuum membrane distillation Number of fibers in membrane module 2-42 Length of membrane module 0.233 m	28% over than the straight hollow fiber	Values not indicated	Simulation study Use of solar energy When the inlet feed temperature is about 80°C, the permeate flux enhancement for the helical configuration is 76%.	[4,18]
Direct contact membrane distillation Number of fibers in membrane module 51 Length of membrane module 0.450 m Fiber outer diameter: 1.45 mm Fiber inner diameter: 0.980 mm Membrane porosity 82-85% Salinity of feed water: 3.5% Permeate flow: 4l/min Permeate temperature: 25°C feed temperature: 70°C	92% over than the straight hollow fiber	Values not indicated	Experimental study	[33]
Vacuum membrane distillation Length of membrane module 0.079-0.79 m Salinity of feed water: 35g/L Vacuum pressure 3000 Pa Feed velocity 0.35 m/s feed temperature: 60°C	20% over than the straight hollow fiber	Increase of pressure drop by 20% than the straight hollow fiber for a feed velocity of 0.35 m/s	Simulation For helical fiber, the positive effect on permeate flux was balanced with additional pressure drop	[34]

(*) Permeate enhancement for helical fiber compared to straight fiber
(**) Increment of pressure drop for helical fiber compared to straight fiber

Vacuum membrane distillation experiments were also carried out with helical fibers to improve process efficiency. It was expected that the occurrence of Dean vortices would increase mass and heat transfer coefficients, thereby causing a drop in temperature and concentration polarization [34]. Indeed, this configuration led to a 20% increase in permeate flux by 20% compared to the obtained value for straight fibers. However, the impact of flux gain derived from Dean vortices is limited when the temperature and concentration polarization phenomena are not very strong.

3. Use of Helical Fiber in Extraction

Hollow fiber cartridges can be used in membrane extraction, and their interfacial area can be 10-fold superior to stirred tanks [35]. Dominguez-Tello et al. [36] used a 3D printer to print a device to facilitate extraction while preserving the helically wound bundle shape. This technique gives the flexibility to perform the extraction with long fibers and to operate with a small sample volume. In addition, good reproducibility and repeatability of all experiments can be ensured, and easy handling of the cartridges can be guaranteed when mounting on the manifold. Another study by Liu et al. [37] compared the efficiencies of both types of design. In this investigation, a helically wound bundle was prepared by winding fiber around a metal rod of constant diameter and maintaining a constant pitch between turns to obtain a helical spiral shape. This fiber was subsequently immersed in a tank filled with a solvent solution made of water saturated with n-butanol. The final phase ended with a drying period spanning a couple of days.

This preparation method produced a robust fiber capable of retaining its helical shape after 20 days of use. Cross-sectional views of these two designs - imaged via scanning electron microscopy- depict a more uniform structure for the straight fiber than the helical fiber [37]. These experimental studies established that the helical fiber's mass transfer coefficient (MTC) values were between 2 and 2.5 higher than straight fibers Figure 4.

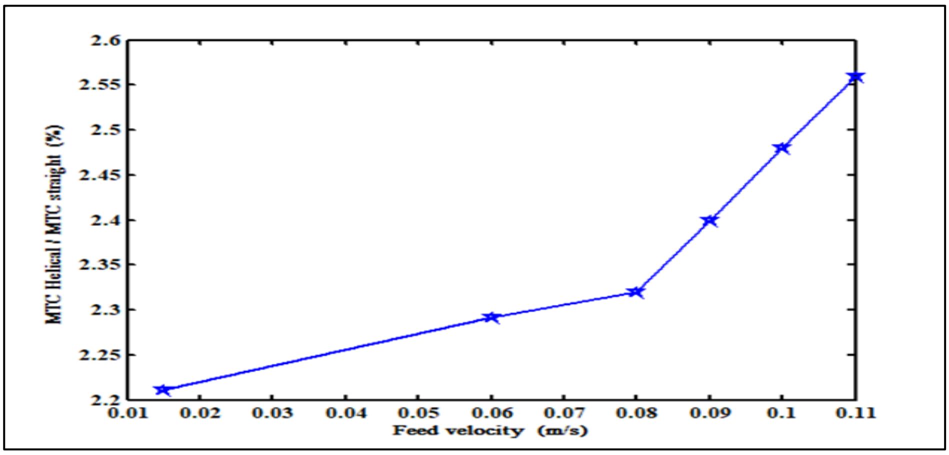


Figure 4: Evolution of the ratio between the helical and linear mass transfer coefficient as a function of the feed rate

This rise can be justified by the increase of turbulence leading to a reduction of the boundary layer on the fiber shell, thereby causing the improvement of the mass transfer coefficient. Therefore, the helical fibers preparation technique, presented by Liu S. H. et al. [37], is very promising since the helical fibers produced maintained their geometrical characteristics after an extended service time while the mass flow properties can be further optimized.

Liu et al. [38] reported the uptake of mass transfer for the helical hollow fiber, considering both its shell and lumen sides. Under the same operating conditions, the helically hollow fibers offer an improved mass transfer coefficient, which is about 3.5 times higher than straight fibers. This improvement was attributed to the secondary flow created inside helical fiber elements and the turbulence generated on the shell side. Similar findings have been presented by Kong et al. [39]. This research work combined a simulation study and some experimental analyses. The membrane module comprised five polypropylene hollow fibers, each having a porosity of 45%, an inner diameter of 0.39 mm, and a length of 0.20 m. These characteristics are the same for the helical and straight modules. These cartridges are tested for a lab-scale installation designed to separate the aromatic impurity p-toluic acid in wastewater, using p-xylene (PX) as an extractant. It was found that the helically wound bundle exhibited an extraction efficiency twice as high as the straight fiber bundle. In addition, for inside-out fiber cartridges – i.e., feed stream flows inside the lumen section of fiber- the helical configuration exhibited higher-pressure drop values versus the straight design, but without additional energy input.

4. Use of Helical Hollow Fibers in Gas/Liquid Applications

The presence of membranes in gas/liquid applications has become increasingly significant, as reflected by the many studies conducted. Singh et al. [40] benchmarked straight and helical fibers for an oxygenation case study. This membrane equipment can be used to deliver oxygen to blood inside the human body. According to this study, the helical fibers exhibited 2.7 times higher permeate flux than the straight fibers. This dramatic augmentation of mass transfer coefficients and permeate flux can be correlated with the effect of secondary flow inside fibers, which leads to an intensification of the mixing of fluids. Additionally, the pressure drop was 2.46 times higher for the helical membrane modules compared to the straight fiber cartridges. This pressure drop uptake increases power consumption, which consequently undermines the benefits of helically wound bundles for this application.

Nagase et al. [41] also experimented with these helical fibers for oxygen transfer from water. This study tested four modules with different arrangements of hollow polypropylene fibers. Helical fibers showed a clear improvement in the mass flow compared with straight fibers due to the increased turbulence. Furthermore, this improvement in flow allowed for a reduction in membrane surface area at the module.

Kaufhold et al. [42] tested the use of hollow fibers with (straight/meander/helical/twisted configurations) in some experiments focused on oxygen separation. It was established that the oxygen mass transfer coefficient for a Reynolds number of 141 was 2.4 times higher for the helical module versus the straight element. This improvement was noticeable, with hollow fibers exhibiting a curvature diameter below 4 mm. For larger diameters, these designs led to a reduction in fiber packing density inside the modules. Luelf et al. [43], who investigated both straight and helical cartridges, reported some sharp advantages that the latter due to reduced concentration polarization, lower surface membrane fouling, and higher mass transfer coefficient values

An artificial gill is a device transporting oxygen from water to air. It enables humans to breathe underwater, thereby extending the time that humans can be spent underwater. Nagase et al. [41] experimented with helical fibers for oxygen transfer from water seeking to utilize them in artificial gill in artificial gill. These researchers benchmarked four modules with different arrangements of polypropylene hollow fibers. As a result, the mass flow coefficients were drastically improved for helically wound bundles compared to straight fiber bundles due to increased flow turbulence. Furthermore, this outcome led to an optimization of permeate flux and reduced the membrane surface area inside the filter cartridges.

Jani et al. [44] tried optimizing the design of a gas-liquid micro-mixer. For this purpose, they developed a gas-liquid separator made of a helical fiber membrane. This micro-contactor presented in Figure 5 is composed of a polypropylene fiber that is helically around a glass tube and characterized by an outer diameter of 2.7 mm, an inner diameter of 1.8 mm, and an average pore diameter of 0.27 µm. This tube is inserted into another tube, thereby forming the shell side. It was shown that for a Reynolds number higher than 60, a mass flow improvement greater than 80% was achieved when comparing the helical versus straight fiber type.

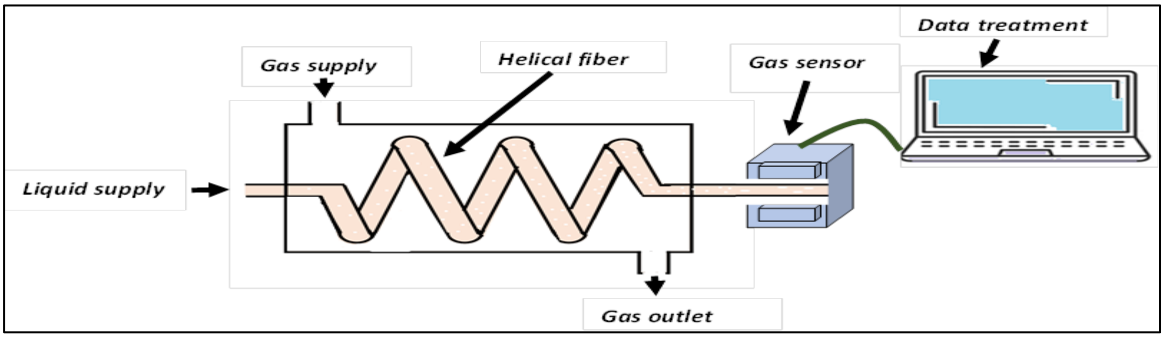


Figure 5: Schematic representation of the experimental setup used for oxygen uptake in water

5. Use of Helical Hollow Fibers in Membrane Filtration Applications

The utilization of helical hollow fibers is also prevalent in filtration processes. It has been reported that their permeate flux can reach 300%-400% of values typical for straight fiber elements. In addition, the pressure drop uptake measured for helical designs was 200%-300% higher relative to straight fiber configurations [45]. Other filtration studies concluded that the permeate flux of helical hollow fiber membranes was five-fold that of straight hollow fibers [46]. This increase can be attributed to secondary flows caused by Dean vortices, which can occur for fluid motion produced in curved channels and above certain critical Reynolds numbers.

Kuakuvi et al. compared the performance behavior of helical and straight hollow fibers while running some ultrafiltration experiments [47]. The membrane modules were made of 20 fibers, corresponding to a full membrane area of 2.0510^{-2} m^2. The inner fiber diameter was 0.7 mm, and its length was 470 mm. The pressure drop was expected to be lower for straight hollow fiber geometries, as highlighted in the above studies – i.e., mainly because of Dean vortices. However, these researchers established that the larger the coil diameter (fiber) for helical membranes, the lower the pressure drop. Moreover, for similar energy consumption levels, membrane modules built with helical fibers gave the highest permeate flux

A comparison between helical and straight hollow fibers was made in the case of filtration of bovine serum albumin (BSA) [48]. The experimental filtration setup is depicted in Figure 6.

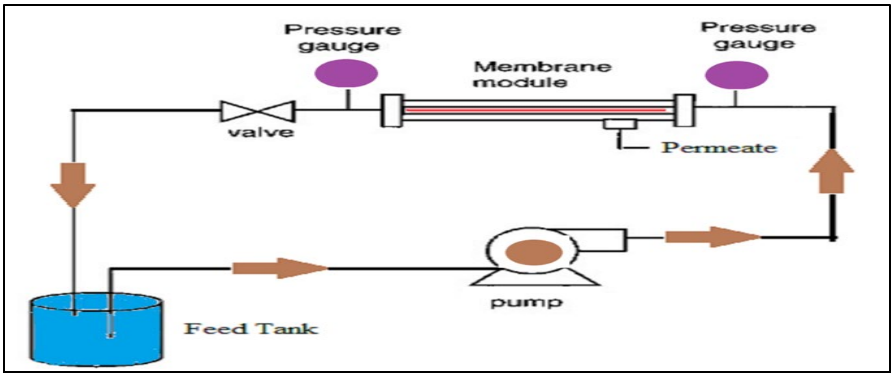


Figure 6: Description of the experimental setup used for membrane filtration

Helical hollow fibers gave a membrane permeability of 227 l/h m² bar for pure water filtration, which is 72% higher than measured for straight hollow fibers. The effect of hollow fiber configurations on filter fouling during BSA filtration has been investigated, with the protein feed stream passing inside or outside the hollow fiber bundles. Results depicting the variation of pressure drop for helical cartridges (PDH) and straight hollow cartridges (PDS) are reported in Figure 7.

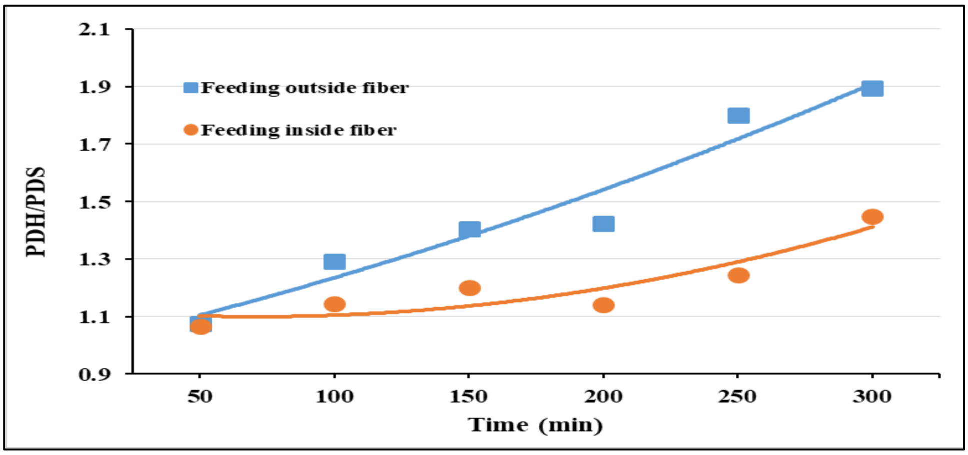


Figure 7: Evolution of the fouling phenomena of the helical fiber compared to the straight fiber with time for the case of inside or outside feeding

For all designs, the progression of fouling as a function of time exhibited an upward trend. For the helical modules, the fouling profile was almost unchanged between inside-out and outside-in BSA feed streams. However, BSA feed stream orientation impacted the fouling behavior for straight modules. When comparing both configurations, helical hollow fibers yielded the highest level of protein fouling, corresponding to a high decrease in permeate flux, an increase in production cost, and a shortened membrane life cycle with time, increasing the production cost and reducing the lifespan of the membrane [13,49,50].

In Table 2, we summarize the comparison between helical and straight hollow fibers for the case of the effects of fiber configurations on permeate flux and pressure drop.

Table 2: Comparison between helical and straight hollow fibers for extraction, gas/liquid, and filtration applications

Operating conditions	PE*	IPD**	Remarks	Ref.
Extraction of disinfection by-products by helical hollow fiber Length of hollow fiber: 10 cm Extraction temperature: 45°C Extraction time: 30 minutes Sample pH:3-4.5	Values not indicated	Values not indicated	Experimental work larger fiber surface for the extraction and a lower sample volume is required when compared to the U- or I-shaped H Good reproducibility is due to the absence of contact between the fiber and the vial surface when using mechanical agitation or effervescence, even with long fiber length.	[36]
Extraction of phenol from the organic phase to the aqueous phase Hollow fiber inside diameter: 1.1 mm The thickness of Hollow fiber; is 0.1 mm Number of fiber: 1 or 4 Spiral pitch: 2 cm Spiral inside diameter: 2 mm	200%-400% over than the straight hollow fiber	Increase of pressure drop by 300% than the straight hollow fiber	Experimental study The permeate flux of the helical hollow fiber increases much faster than that of the straight hollow fiber module. This is due to the impact of the secondary flow in the helical hollow fiber The pressure drop in the helical hollow fiber increases much faster than in the straight hollow fiber	[37]
Gas/liquid application Length of hollow fiber membrane module: 140-280 mm Fiber outer diameter: 700/1100 µm Fiber inner diameter: 500/800 µm Hollow fibers number: 15-82 Wind angle 30°-90°	200%-350% over than the straight hollow fiber	The pressure drop of helical hollow fiber increases by 17% compared to the value obtained for straight hollow fiber	A numerical and experimental study. An increase of permeate flux of about 200% for the flow outside of the helical hollow fiber	[38]

Table 2: Continued

Extraction of the aromatic impurity p-toluic acid in wastewater of terephthalic acid production process Hollow fiber in Poly-propylene Fiber outer diameter: 490 µm Fiber inner diameter: 390 µm Fiber length: 1 m Membrane porosity 45% Curvature diameter of helical fiber: 6.5 mm Number of fibers in membrane module: 5 Pitch of helical fiber: 3 mm	100% over than the straight hollow fiber	For flow inside fibers, helical fibers have a higher pressure drop of about 11% compared to straight fibers For the shell-side flow, a negligible difference in pressure drop is noticed between the helical and straight fibers.	Numerical and experimental study The use of helical fibers instead of straight fibers will achieve double p-toluic acid wastewater treatment efficiency.	[39]
Gas/liquid application Length of membrane module0.71-2.58 m Fiber inner diameter: 3.2 mm Curvature diameter of helical fiber: 24.8-32 mm	270% over than the straight hollow fiber	246% over than the straight hollow fiber	Simulation study .	[40]
Gas/liquid application Hollow fiber in Poly-propylene Membrane surface area: 1.9-2.4 m² Fiber outer diameter: 0.250-0.380 mm Fiber inner diameter: 0.190-0.300 mm Pitch of hollow fiber: 0.350-0.580 mm	straight hollow fiber is preferred over helical	Values not indicated	Experimental and Simulation study. Straight hollow fibers are preferred to helical hollow fibers for oxygen release Helical hollow fiber arrangement is preferred for fluids flowing inside hollow fibers	[41]
Gas/liquid application Hollow fiber in Poly-propylene Fiber outer diameter: 1 mm Fiber inner diameter: 0.6 mm Fiber length 5-30 cm Curvature diameter of helical fiber: 5-19 mm Pitch of hollow fiber: 2 mm	140% over the straight hollow fiber.	Increase of pressure drop by 200 mbar	Simulation and experimental study Helical geometry does not apply to large-scale modules. Setup time for such fiber geometries and module costs would outweigh the benefit of mass transport	[42]
Gas/liquid application Hollow fiber in Poly-propylene Fiber outer diameter: 2.7 mm Fiber inner diameter: 1.8 mm Pore size: 0.27 µm Pitch of hollow fiber: 40 mm Curvature diameter of helical fiber: 2.5 mm	Permeate flux was greater than 80% in the helical fiber compared to the straight fiber.	Values not indicated	Experimental and Simulation study. Gas uptake in liquid flowing inside helical fiber was higher compared to the straight fiber	[44]
Filtration application Dimensionless coil radius: 20 dimensionless pitch: 69	300-400% over the straight hollow fiber during microfiltration of yeast.	Two to three times higher than the value obtained for the straight hollow fiber	Numerical study	[45]
Filtration application Hollow fiber in Poly(ether sulfone) Fiber outer diameter: 0.778-1.285 mm Fiber inner diameter: 0.519-.618 mm Pore size: 1.8 µm Pitch of hollow fiber: 1.2-2.8 mm	Permeate flux was greater than 72% in the helical fiber compared to the straight fiber.	1.5 to 2 times higher than the value obtained for the straight hollow fiber	Experimental study. Bovine Serum Albumin rejection is greater by 3% for helical fiber when compared to the straight fiber	[48]

(*) Permeate enhancement for helical fiber compared to straight fiber
(**) Increment of pressure drop for helical fiber compared to straight fiber

6. Long-Term Application of Helical and Straight Hollow Fibers

When exploring the long-term use of both hollow fiber configurations (straight and helical types), Baldridge et al. [51] concluded that there was no significant change in efficiency after a couple of days of air filtration. However, Liu et al. [29] established that after running an extraction process for more than 20 days, straight modules experienced an increase in the fiber length, which caused some performance loss because of the distorted bundle [37]. Conversely, the membrane characteristics of helical modules remained unchanged after 20 days of operation. In summary, these two research programs suggest that gentle processes (e.g., air filtration) have a lesser impact on membrane properties during extended service operations. But more intrusive (liquid) processes will yield greater mechanical stress on the membranes; in this case, the helical design proves to be the preferred option – i.e., versus straight fibers Liu et al., [37].

7. Conclusion

The interest in membrane processes has been steadily growing for several decades due to many attractive features such as their ability to separate or concentrate species, modularity, controllable footprint, ease of operation, and compliance with other technologies. However, the most outstanding challenge is balancing the minimization of fouling phenomena and energy consumption with increased permeate flux and membrane retention properties. Many studies have explored several types of hollow fiber membranes to address these shortcomings, including the straight and helical hollow fiber designs. A comparative analysis between these two configurations targeted several applications, including extraction, desalination, gas/liquid applications, and filtration processes.

The attractiveness of helically wound fiber membranes highlighted by this review results from their mechanical robustness and intrinsic ability to promote flow turbulence. These attributes often lead to faster permeability rates, reduced concentration polarization, and fouling propensity stable performance over the extended service life, thus favoring the helical modules over the straight ones. Future work should consider a more systematic exploration of the relationship between the helical fiber structure and its pressure drop in targeted applications. Furthermore, the adoption of modeling tools could be extremely beneficial in correlating the hollow fiber membrane structure (straight and helical types) with their functional properties in terms of flow rate-pressure drop profiles, retention efficiencies, and fouling characteristics

Author contribution

A.Zrelli; writing—original draft preparation, J.Debaya; software image treatment, A. Doucoure; review and editing, B. Chaouachi; analysis.

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

Authors declare that their present work has no conflict of interest with other published works.

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