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Rope coiling spinning of curled and meandering hollow-fiber membranes

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ABSTRACT

Curved and structured membrane geometries are known to have the potential to reduce concentration polarization and fouling rates in membrane filtration and membrane contacting applications. However, their production is cumbersome and often comprises various successive processing steps. We present a new direct fabrication process of two new hollow fiber geometries: Curled and meandering hollow fibers. The phenomenon of liquid rope-coiling is adapted to a membrane spinning process resulting in mostly spiralling curly fiber geometries. Parameters influencing geometric properties are evaluated and experimentally obtained structures are presented. Fibers were prepared from a polyethersulfone-based polymer solution in an air gap spinning process. Prepared structured hollow fibers are investigated regarding geometrical measures and pore structures. A comprehensive analysis of the complex interplay between the influencing parameters is suggested.

1. Introduction

Hollow fiber membranes are widely used in industrial applications such as gas separation [1], gas absorption [2], microfiltration [3] and ultrafiltration [4], hemodialysis and nanofiltration [5]. Today's industrial products generally have a simple geometry: The cross-section is almost perfectly circular and the axial geometry is straight. For hemodialysis applications, hollow fibers are slightly undulated in order to facilitate equal wetting of the fiber shell with dialysate over all fibers. For reasons of mass transport enhancement, some publications report more complex geometries of the membranes to influence the hydrodynamics inside or outside the tubular, capillary or hollow fiber membranes. Examples are:

- Microstructuring the inside or the outside of hollow fibers [6].
- Templating of flow channel geometry of monolithic structures [7,8].
- Winding fibers around an inner core for polymeric and ceramic membranes [9–11].
- 3D printed membrane surfaces based on triple periodic minimal surfaces [12,13].

In particular, spiralling geometries have been of interest because they induce secondary flows on the inside and provide non-parallel flow on the outside of the fiber [14]. Such spiralling geometries are difficult to fabricate in a continuous and scalable membrane production process. Mostly, such geometries are simply made by winding the tubular or fiber membrane around a core. It is therefore of interest and relevance to investigate whether today's hollow fiber production methods can be tailored easily to fabricate such geometries. Here we present a method to fabricate spiralling and meandering hollow fiber membranes based on a classical membrane spinning process. The method is based on the liquid rope coiling effect and can be observed when a liquid jet passes a low viscosity environment and impacts on a more viscous phase or surface [15,16].

We suggest to alter the classical liquid rope coiling phenomenon of a polymer solution as illustrated in Fig. 1: (a) instead of a solid surface we use the liquid surface of the coagulation bath, (b) the liquid rope coiling occurs with a superimposed phase separation, and (c) the extruded and falling polymer solution comprises a coextruded jet of polymer solution with an internal coagulant lumen.

Rope coiling effects are reported in the literature for (chaotic) formation of curled full fibers in electrospinning processes [18,19] and dry jet wet spinning [20]. An approach for continuous production of hollow fiber membranes has not been reported until now. This paper focuses on the process parameters influencing the stability of the liquid rope coiling process as well the morphological consequences of the liquid rope coiling process on the membrane morphology.

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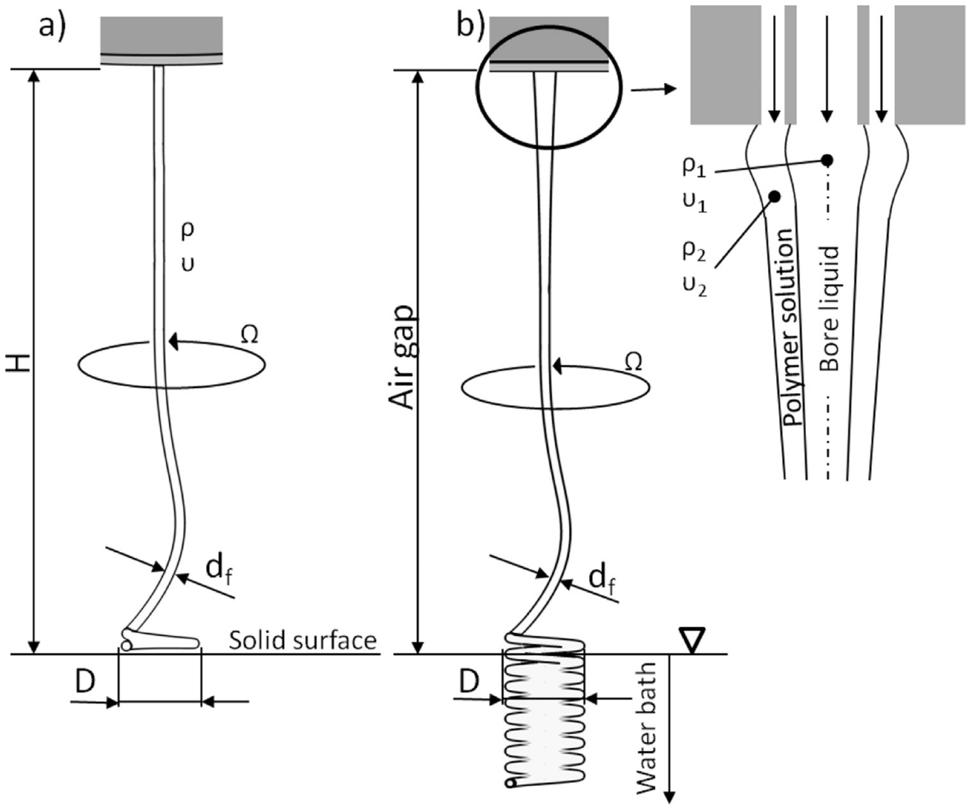

Fig. 1. Schematics of rope-coiling setups: (a) classical rope-coiling set-up with a solid surface and a single jet, adopted from Ribe [17]. (b) Rope-coiling set-up with a viscous bath and a co-extruded jet.

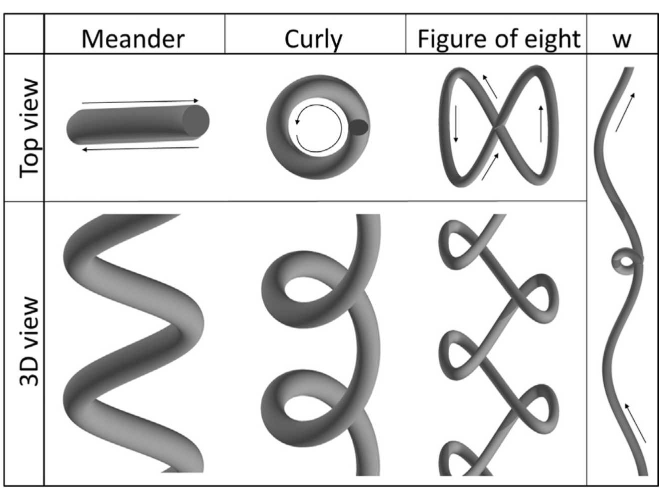

Fig. 2. Fundamental curl states reported in literature. (a) Meandering rope coiling, (b) spiralling rope coiling, (c) figure of eight, (d) w-pattern. States (a)–(c) can be observed in a free falling situation. The w-pattern (state (d)) occurs when the falling liquid hits on a moving surface.

In hollow fiber spinning, membrane shapes are formed from a polymer solution in form of a viscous jet prior to phase separation. The periodic alignment of viscous jets on solid surfaces has been investigated in numerous publications since the 1960s [21]. The observed phenomenon is described as liquid rope coiling, where the viscous jet aligns after falling on a surface. In recent investigations two main set-ups have been used. In the first one, a viscous jet falls from an adjustable falling height on a solid surface. In a second set-up the solid surface is replaced by a horizontal moving belt, thus adding one degree of freedom to the system. In case of zero belt speed, both setups are obviously equal. There are numerous rope coiling phenomena observed in these investigations. The most stable and most often observed ones are a spiral alignment and meandering of the jet. Different sub-states of those exist, which can be interpreted as a combination of these two phenomena as shown in Fig. 2. Here we investigate (a) whether liquid rope coiling can be used to fabricate spiralling hollow fiber membranes and (b) how process and solution parameters influence the geometrical and morphological characteristics.

2. Background

2.1. Applications of spiral channels

Spiral structures are already widely used in process industry in terms of enhanced heat transfer [22].

Spiral hollow fiber arrangements have been subject to research in several applications. According to Carstensen et al. [23] spiral hollow fiber arrangements are used in situ product removal in biotechnology, both in submerged and closed loop configurations. Luque et al. applied a hollow fiber, wrapped around a glass support in filtration of yeast cells and observed an improvement of flux and capacity by factors up to 3.9 [9]. Kaufhold et al. investigated oxygen transfer at spiral and meandering single fiber gas–liquid contactors and measured an increase of oxygen transfer rate of up to 2.4-fold [24].

In process industry spirally hollow fibers may be applied in the fields of chemical reactors (microreactors), enhanced membrane operation and absorption processes, wastewater treatment and oxygenation [22,25,26].

2.2. Enhanced mass transport inside a spiral channels

In a curved flow channel centrifugal forces act on a fluid