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A mini-review on release oscillation in a hollow fiber

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This mini-review aims at strengthening the links among textile science, physics, and mathematics. The state-of-the-art technology for silver ions' release from hollow fibers is reviewed, its bottleneck problems are identified, and some open problems are elucidated. The release oscillation opens a new era for modern applications of hollow fibers containing silver ions.

KEYWORDS

hollow fiber, ions release, capillary rise, antibacterial property, nanofluid, fractal, fractional calculus (FC)

1 Introduction

Hollow fibers have obvious advantages in that they are low density and have good flexibility. Natural hollow fibers have even more amazing properties, for example, polar bear hairs have remarkable thermal properties [1, 2]. Wang et al. elucidated the biomechanism of the hollow hair of the polar bear using the fractal calculus with great success [3], Cui et al. designed a biomimetic textile with good thermal insulation [4], and Liu et al. found a new phenomenon of thermal oscillation in the thermal insulation [5]. Hollow-fiber liquid-phase microextractionare is highly efficient for extraction of heavy metals and pharmaceuticals [6–8]. The corresponding solvent, which should be of low polarity and immiscible with water, is immobilized in the pores in the wall of hollow fibers and serves as a supported liquid membrane. A larger number of reports have been published on the development of hollow fibers as a green sample preparation technique requiring only a few microliters of organic solvent per sample. Due to the protection of the acceptor phase by the supported liquid membrane, hollow fibers are amenable to highly complex samples such as plasma, whole blood, urine, saliva, breast milk, tap water, surface water, pond water, seawater, and soil slurries [9].

The physical process of hollow fiber spinning always involves four steps: solution formulation, extrusion, coagulation, and coagulated fiber treatment [10]. Thus far, the electrospinning technique has been considered as a versatile and efficient method for the fabrication of membranes with highly interconnected pore structures [11]. The flexibility of device construction for electrospinning and the diversity of the post-treatment process to electrospun membrane leaves vast scope for researchers to tailor the membrane structures and properties; thus, polymeric nano-scale hollow fibers via electrospinning technology have become popular, for example, bubble electrospinning might be a good candidate for hollow fiber fabrication [12, 13].

This paper focuses on artificial hollow fibers containing silver particles [14, 15], with an emphasis on the release oscillation [16–18].

2 Antibacterial mechanism

Hollow fibers containing silver ions are widely used for antibacterial and antifouling applications [19, 20]; when the fibers are submerged in water, silver ions are gradually released from the inner wall into the water.

Viruses and bacteria are generally quite small [21–23]. In particular, some deadly viruses (e.g., the COVID-19 virus) have a complex unsmooth surface, and a small surface has high surface energy (geometric potential) [24–26], which can easily absorb silver nanoparticles around the surface. The absorbed nanoparticles make viruses and bacteria inactive [24].

On the other hand, silver ions react with water when ions are adhered to the surface of bacteria or viruses:

$$Ag^{+} + H_2O \rightarrow AgOH + H^{+} \tag{1}$$

Bacteria and viruses will be killed due to their exsiccosis and hydrogen ions can react with macromolecules, which is the mechanism of the antibacterial property of the hollow fibers containing silver ions. Of course, however, a high concentration of silver ions will be also harmful to human cells.

3 Capillary effect and diffusion process

The inner diameter of hollow fibers greatly affects the ions release. A smaller diameter implies a higher capillary rise [27, 28]; as a result, more ions can dissolve in water and the diffusion process makes the ions release into the outside of the hollow fiber. Han and He unlocked the secret of hollow fibers' antifouling properties using the capillary effect [29]. Environmental temperature and saline water will affect the ions' diffusion process [30–33].

Though hollow fibers with thinner diameters have better capillary effect, the corresponding fabrication needs more costs, meanwhile, the inner wall surface area is less, so there are less loaded ions. The effects of the temperature on the diffusion process and viruses and bacteria's metabolism should also be considered, as well as additionally the nanofluid mechanics [34–37] being of paramount importance in studying the optimal design of the hollow fiber's geometrical structure and its effect on its antibacterial properties.

4 Release oscillation and frequency property

Due to environmental perturbation, the water in hollow fibers is vibrated periodically, the mechanism of which was first found in [17]. The vibrating water accelerates the release process; however, the non-linear vibrations make it difficult to predict its frequency properties. The governing equation can be expressed as [17].

$$\frac{d^2u}{dt^2} + \frac{a+bu}{(L_0-u)(u+u_0)} = 0 \tag{2}$$

with initial conditions

$$u(0) = 0, u'(0) = A \tag{3}$$

where u is the capillary rise, a, b, and L_0 are constants. The physical understanding represented by each physical parameter is referred to reference [17], and A is the initial velocity.

Solving Eq. 2 effectively is still an open problem. The possible methods to solve Eq. 2 with the initial conditions of Eq. 3 include mainly the homotopy perturbation method [38, 39], the Li-He method [40–42], frequency-amplitude formulation [43], and the variational principle [44].

For u, Eq. 2 can be approximately expressed as

$$\frac{d^2u}{dt^2} + \frac{a+bu}{u_0L_0}\left(1+\frac{u}{L_0}\right)\left(1-\frac{u}{u_0}\right) = 0 \tag{4}$$

or

$$\frac{d^2u}{dt^2} + \frac{a}{u_0L_0} + \frac{1}{u_0L_0}\left(\frac{a}{L_0} - \frac{a}{u_0} + b\right)u + \frac{1}{u_0L_0}\left(-\frac{a}{u_0L_0} + \frac{b}{L_0} - \frac{b}{u_0}\right)u^2 - \frac{b}{(u_0L_0)^2}u^3 = 0 \tag{5}$$

This equation was studied in [45]; the quadratic non-linearity will gradually consume the vibrating energy, and finally the vibrating motion will stop (see the discussion in [46]).

5 Fractal-fractional model for ions release

The unsmooth surface of the inner wall of the hollow fiber is another important factor affecting the release process. Because any physical laws are scale-dependent, the same phenomenon may lead to debating theories if observed using different scales [47]. Capillary effect plays an important role in the heat transmission of porous media and capillary vibration significantly affects the capillary rise or capillary pressure; therefore, the mass transfer or heat transfer will be greatly affected [48]. Most capillary vibrations in the literatures have assumed that the capillary tube is small and uniform; however, capillary tubes are non-uniform in most porous media [24, 48]. The capillary fluid moves extremely slowly, and its vibrations near its equilibrium have an extremely low frequency [48]. Owing to two types of capillary pressures (positive capillary pressure and negative capillary pressure), the capillary pressure from porous media should be taken into consideration [11]. Furthermore, capillary pressure is affected by pore size, capillary pressure with different pore sizes has been analyzed for the hydrophobic-hydrophilic interface in detail, such as electrospun hollow nanofibers used in oil/water separation [11].

The capillary effect has wide applications for microelectromechanical systems and microfluidics devices, in which the capillary vibration significantly affects its mass transmission [48]. Nanofluid mechanics can be directly used for describing the releasing process for the smooth boundary, so the unsmooth boundary makes the release more difficult, but it is amazing Wolfgang Pauli (1900–1958) once said that "God made the bulk, the surface was invented by the devil". The unsmooth surface determines the release process and it can be modeled by the two-scale fractal dimension [49] with ease. In the fractal space, Liu et al. established a fractional model for the silver ions' release oscillation [50]. The fractal-fractional model offers a new window for studying the effect of the unsmooth boundary on the release process. Fan et al. concluded that the fractal calculus plays an important role in unlocking the mechanisms of natural fibers [51]. Lu et al. provided two numerical approaches for finding the approximated solutions of the time fractional Boussinesq-Burgers equations without any linearization or complicated computation, including the homotopy perturbation transform method and the method based on the fractional complex transform and homotopy perturbation method [52]. Afterwards, a numerical approach was proposed for finding the approximated solutions of a fractal modification of the Yao-Cheng oscillator based on the two-scale fractal transformation and the global residue harmonic balance method with He's fractal derivative as well [53]. They also proposed a combined technique for solving the fractional modification of the non-linear oscillator with coordinate-dependent mass [54]. Meanwhile, the numerical sensitive analysis of the approximations were further considered with respect to different amplitudes and parameters, confirming their high efficiency and stability [53, 54]. Considering that two-scale thermodynamics observes the same phenomenon using two different scales, fractal calculus is adopted to establish governing equations, and fractal variational principles are discussed for 1-D fluid mechanics [47], modeling the ions' release process from an unsmooth boundary of the inner wall of the hollow fibers might be possible.

6 Conclusion

Hollow fibers are now a research Frontier in textile engineering, nanofluid mechanics, material science, non-linear science, physics, and mathematics. This mini-review article provides a panoramic view of the recent studies in this meaningful direction. It is still an open problem to model the ions' release process from an unsmooth boundary of the inner wall of the hollow fibers; a mathematical model for the fractal release oscillation might be more attractive and promising. There is much opportunity and challenge, so this article should be the beginning of future research, not only a review.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Conflict of interest

Author YL works at Zhejiang Sci-Tech University, and also is a joint postdoctoral fellow of Laimei Technology Co., Ltd., Changxing

The remaining author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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