frontiers | Frontiers in Physics

TYPE Mini Review
PUBLISHED 06 October 2023
DOI 10.3389/fphy.2023.1251608

Check for updates

OPEN ACCESS

EDITED BY
Chun-Hui He,
Xi'an University of Architecture and Technology, China

REVIEWED BY
Naveed Anjum,
Government College University, Faisalabad, Pakistan

*CORRESPONDENCE
Yu Liu,
liuyu@suda.edu.cn

RECEIVED 02 July 2023
ACCEPTED 19 September 2023
PUBLISHED 06 October 2023

CITATION
Liu Y, Chen H and Chen L (2023), The mechanism of the capillary oscillation and its application to fabrics' sweat permeability.
Front. Phys. 11:1251608.
doi: 10.3389/fphy.2023.1251608

The mechanism of the capillary oscillation and its application to fabrics' sweat permeability

Yu Liu[1,2]*, Hongxia Chen[3] and Lifen Chen[2]

[1]National Engineering Laboratory for Modern Silk, College of Textile and Clothing Engineering, Soochow University, Suzhou, China, [2]Jiangsu Sunshine Group, Wuxi, Jiangsu, China, [3]Department of Laboratory and Equipment Management, Soochow University, Suzhou, China

The capillary effect plays an important role in air and moisture permeability, and it can be used for thermal enhancement and energy harvesting. However, the capillary oscillation has not been extremely studied, and its mechanism for fabrics' sweat permeability was rare and preliminary. This paper studies the frequency property of the capillary oscillation in a zig-zag porosity of a fabric with a multiple layer structure. The theoretical analysis reveals that small porosity and low frequency of the zig-zag porosity are beneficial to the high sweat permeability. The proposed capillary oscillation probably paves a new avenue for designing fabrics with high moisture permeability, particularly in sportswear and military apparel in extreme cold environments.

KEYWORDS

capillary flow, capillary oscillator, low-frequency property, sweat permeability, fabric, hierarchical structure

1 Introduction

The capillary effect [1–3] appears everywhere in our everyday life and engineering, and the capillary fluid [4] can be used for enhancing heat conduction in micro/nanodevices or in a porous hierarchy [5, 6]. The capillary effect can also be effectively applied in the microelectromechanical system (MEMS) [7, 8] and energy-harvesting devices [9, 10] and can greatly affect the mechanical and thermal properties of porous materials [11–14]. The application of capillary oscillation to fabrics' sweat permeability has significant implications in textile engineering. Sportswear garments that are designed with high sweat permeability are preferred to enhance breathability and prevent excessive moisture buildup. This is crucial as excessive moisture buildup can lead to discomfort and distraction during physical activity, ultimately hindering the performance of the wearer. Similarly, garments with excellent sweat permeability are necessary to allow for rapid absorption of sweat and minimize skin irritation in undergarments. The fabrics' sweat permeability from the inner side to the environment has triggered rocketing interest in sportswear and military apparel in an extreme cold environment. If the sweat cannot be transferred through the cloth after an active motion, it will greatly affect the comfort property and even be life-threatening due to the icy fabric.

The capillary oscillation and its relationship with sweat permeability are crucial for developing new materials with improved performance characteristics in textile. However, the capillary fluid's oscillation property was hardly analyzed. Jin et al. revealed the frequency property mathematically [1]. Han and He applied the capillary oscillation to fabric's self-cleanliness [15]. Xiao, et al. studied the capillary oscillation in a short small tube [16]. Saxena studied moisture permeability through nylon and cotton fabrics [17]. Midha et al. researched the laundering times on moisture permeability [18]. As the capillary thread moves up and down, it displaces a small amount of liquid from the surface of the fabric into the surrounding air. The process reduces the local surface tension at the contact point between the fabric and the skin, making the fabric more hydrophilic and thus more susceptible to sweat absorption. Ha et al. showed that air and moisture permeability plays an important role in the clothing microclimate [19]. Raja et al. conducted an experiment on the sweat transfer of multi-weave structure fabrics [20]. Guan et al. studied the clothing–human body system [21]. Liu et al. researched the thermal property of a microstructure [22]. The oscillatory motion of the capillary wall can create micro-cracks and pores in the fabric, which can facilitate the passage of sweat molecules and enhance sweat permeability. Furthermore, these micro-cracks can also provide additional channels for moisture transfer from the skin to the surrounding environment, further improving sweat evaporation and cooling performance.

All the aforementioned theoretical and experimental studies revealed that the capillary effect on fabrics' sweat permeability is of extreme importance for both everyday life and advanced applications. When sweat interacts with a fabric surface, capillary oscillation enhances the transfer of sweat from the skin to the fabric's surface. This process results in increased sweat permeability, which is essential for regulating body temperature. In this paper, we will show the mechanism of the capillary oscillation and its great effect on the fabric's air/moisture permeability.

2 Capillary oscillation

When a small tube is gradually immersed into a fluid, the fluid rises along the tube. This phenomenon, commonly referred to as the capillary effect [2, 3], is a familiar observation to anyone who has witnessed the wetting process of a napkin when it comes into contact with water. It can be explained by the geometrical potential theory [23]. The capillary rise is vulnerable to an environmental perturbation, and the capillary fluid will vibrate periodically [1]. The periodicity of the capillary oscillator is determined by the combined action of the gravity and surface tension of the liquid, and this periodicity is more obvious in the pull-in solution. Pull-in instability and periodic behavior are two key phenomena in microelectromechanical system (MEMS) dynamics, and differential equations can well describe these nonlinear aspects [24–26]. The capillary rise without any perturbation can be expressed as [27].

$$h \propto \frac{1}{r^n}, \tag{1}$$

where h is the capillary rise, r is the equivalent capillary radius, and n is a positive parameter depending on the tube's geometry.

Equation 1 shows that a smaller porosity leads to a higher capillary rise, which can explain why a nanofiber membrane has high permeability [28]. The nanofiber membrane can be produced via the electrospinning technology [29] and has the potential application in optimizing design of the sportswear and military apparel in an extreme cold environment.

A mathematical model was established in Ref. [1], and Bin et al. conducted a numerical simulation of the capillary oscillation [2].

The dynamical motion of the capillary fluid through a zig-zag porous structure of a fabric can be modelled using the following equation [1]:

$$x'' + \varepsilon \sin(\omega x) + \omega_0^2 x = 0, \ x(0) = A, \ x'(0) = 0, \tag{2}$$

where x is the center of the capillary fluid when it is still, ω is the frequency of zig-zag porosity, ω_0 is a parameter relative to the capillary effect, ε is a geometric parameter relative to fabric's geometry, and A is the amplitude.

When $\omega_0 = 0$, Eq. 2 becomes a famous pendulum oscillator [30]. When x<<1, Eq. 2 can be approximately expressed as

$$x'' + (\varepsilon\omega + \omega_0^2)x - \frac{1}{6}\varepsilon\omega^3 x^3 = 0, \ x(0) = A, \ x'(0) = 0. \tag{3}$$

This is the duffing oscillator [31]. To provide insights into the periodic property of Eq. 3, we quote the frequency formulation of Ji-Huan He [32, 33]. Consider a general nonlinear oscillator in the form

$$x'' + p(x) = 0, \ x(0) = A, \ x'(0) = 0, \tag{4}$$

where p is a nonlinear function of x and $p/x > 0$. Ji-Huan He's frequency formulation reads [32, 33].

$$\Omega^2 = \left\{\frac{p(x)}{x}\right\}\Big|_{x=\frac{\sqrt{3}}{2}A}, \tag{5}$$

where Ω is the frequency of the nonlinear oscillator.

The square of the frequency of Eq. 3 is

$$\begin{aligned} \Omega^2 &= \left\{\frac{(\varepsilon\omega + \omega_0^2)x - \frac{1}{6}\varepsilon\omega^3 x^3}{x}\right\}\Big|_{x=\frac{\sqrt{3}}{2}A} \\ &= \left\{\varepsilon\omega + \omega_0^2 - \tfrac{1}{6}\varepsilon\omega^3 x^2\right\}\Big|_{x=\frac{\sqrt{3}}{2}A} \\ &= \varepsilon\omega + \omega_0^2 - \frac{1}{8}\varepsilon\omega^3 A^2, \end{aligned} \tag{6}$$

where Ω is the capillary fluid's vibrating frequency and A is the amplitude. This frequency formulation is a simple yet effective tool for the fast and accurate identification of the periodic property of a nonlinear oscillator [34–36]. Eq. 4 can also be derived using various numerical methods, such as the homotopy perturbation method [37, 38], the variational iteration method [24, 39], Wang's variational approach [40], or asymptotic methods [25, 26].

3 Fabrics' sweat permeability

A higher vibrating amplitude of the capillary motion implies that sweat can be transferred to a farther distant. When the capillary rise is less than the thickness of the fabric, the capillary oscillation is the main factor for the sweat permeability. According to Eq. 4, a higher amplitude requires a low frequency, and this low-frequency property is the mechanism underlying the sweat permeability. The period of the capillary oscillation is

$$T = \frac{2\pi}{\Omega} = \frac{2\pi}{\sqrt{\varepsilon\omega + \omega_0^2 - \frac{1}{8}\varepsilon\omega^3 A^2}}, \tag{7}$$

where A is the amplitude of the capillary fluid's periodic motion. According to Eq. 7, a large amplitude implies a large period, which infers an extremely slowly motion. This can explain why the capillary rise seems to be stable at the initial stage when the

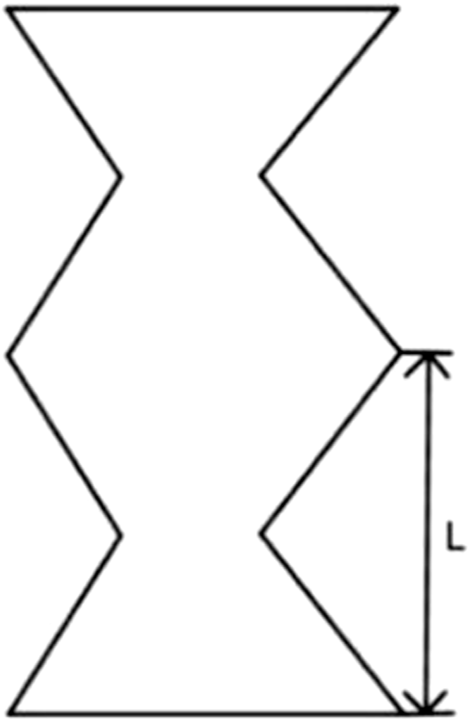

FIGURE 1
Zig-zag capillary tube.

small tube is immersed into water and keeps convincingly unchanged for few hours; however, it might change after 24 h or longer. As the permeability thickness reaches h+A, where h is the capillary height, the capillary fluid's periodic motion will continue to oscillate within the capillary. This oscillation will cause the fluid to move back and forth along the length of the capillary, creating a wave-like motion. A will increase as the thickness of the permeability increases, leading to an increase in the overall flow rate through the capillary. When the fabric's thickness is less than $h+A$, a good permeability is predicted.

The maximal amplitude of the capillary fluid reaches when the frequency becomes zero:

$$\Omega = \sqrt{\varepsilon\omega + \omega_0^2 - \frac{1}{8}\varepsilon\omega^3 A^2} = 0. \tag{8}$$

The maximal amplitude reads

$$A_{\max} = \sqrt{\frac{8\left(\varepsilon\omega + \omega_0^2\right)}{\varepsilon\omega^3}}. \tag{9}$$

Equation 9 shows that the frequency of zig-zag porosity is the main factor affecting the moisture/air permeability.

4 Fabrics with multiple layers and hierarchical structure

To ensure good sweat permeability, the fabric should have a large zig-zag period, as shown in Figure 1.

$$L = \frac{2\pi}{\omega}, \tag{10}$$

where L is the zig-zag period. A larger L leads to a thicker fabric, and the multiple-layer structure is always adopted in practical applications.

In order to decrease the thickness of the fabric with good air/moisture permeability, we can adopt a hierarchical structure from a nano/micro-inner layer to a macro-outside layer, and the thickness of each layer should satisfy the following inequality 11:

$$H_n < r_n + \sqrt{\frac{8\left(\varepsilon_n\omega_n + \omega_{n0}^2\right)}{\varepsilon\omega_n^3}}, \tag{11}$$

where H_n is the thickness of the nth layer of the hierarchy, r_n is the nth layer's capillary rise, and ω_n is the zig-zag frequency of the nth layer [1].

The inner wall of blood vessels is unsmooth, leading to a zig-zag inner surface, so that the blood can be transferred to a farther distance than that of the smooth inner surface.

If the porosity is smooth enough in each layer, inequality 11 should be modified as

$$H_n < r_n, \tag{12}$$

which means the thickness of each layer should be less than its capillary rise. Many natural hierarchical systems can transport water for a long distance [41].

5 Conclusion

This paper proposes the capillary oscillation model to design hierarchical fabrics with good air/moisture permeability, which is of critical importance for the clothing design, especially for sportswear and military apparel in an extreme cold environment, where the sweat permeability plays an important role in human's comfort and safety. This theoretical analysis enables scientists to understand the capillary oscillation and its role in air/water transportation. Capillary oscillation is the periodic oscillation of liquid in a capillary tube due to the interaction between surface tension and viscous forces. In the context of fabric moisture absorption and perspiration, capillary oscillation plays an important role in determining the wicking and transport of moisture in the fabric. When a fabric comes into contact with moisture, capillary forces cause the liquid to be drawn into the fabric's capillary channels. The capillary oscillation then helps distribute the moisture throughout the fabric, allowing it to be absorbed and transported more efficiently. This is because the oscillation creates a pumping effect that helps move the liquid through the capillary channels. In addition, capillary oscillation can also help enhance the fabric's moisture absorption and perspiration properties. By promoting the movement of moisture through the fabric, capillary oscillation can help increase the rate of moisture absorption and perspiration, thereby improving the fabric's overall comfort and performance. Overall, the relationship between capillary oscillation and moisture absorption and perspiration properties of fabrics is complex, with many factors influencing the process. However, it is clear that capillary oscillation plays an important role in determining the wicking and transport of moisture in the fabrics and can help enhance the fabric's moisture absorption and perspiration properties. Understanding this relationship and applying advanced techniques like nanotechnology and optimized yarn structure can lead to the development of innovative textile materials with superior sweat permeability and performance. Because this paper gives a self-contained theoretical model for the sweat permeability for the first time, the future holds exciting possibilities for improving garment design and enhancing human wellbeing as technology advances and researchers continue to explore this topic.

Author contributions

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

Funding

This work was supported by the Large-scale Scientific Instruments Open and Shared Independent Research Project of Jiangsu Province (TC2023A042), National Nature Science Foundation of China (51403146), and Nature Science Foundation of Jiangsu Province (BK20161288).

Conflict of interest

Authors YL and LC were employed by the company Jiangsu Sunshine Group.

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

References

1. Xiao J, Liu MN, Pan F, Li YP, Fan J. Low frequency of a deforming capillary vibration, part 1: Mathematical model. *J Low Freq Noise V A* (2019) 38(3-4):1676–80. doi:10.1177/14613484198562

2. Bin C, Lu JF, Xia ZZ. Numerical investigation of the fractal capillary oscillator. *J Low Freq N A* (2023) 42(2):579–88. doi:10.1177/14613484221131245

3. Pasandideh-Fard M, Qiao YM, Chandra S, Mostaghimi J. Capillary effects during droplet impact on a solid surface. *Phys Fluids* (1996) 8(3):650–9. doi:10.1063/1.868850

4. Deegan RD, Bakajin O, Dupont TF, Huber G, Witten TA. Capillary flow as the cause of ring stains from dried liquid drops. *Nature* (1997) 389(6653):827–9. doi:10.1038/39827

5. Liu FJ, Zhang T, He CH, Tian D. Thermal oscillation arising in a heat shock of a porous hierarchy and its application. *Facta Univ-ser Mech* (2022) 20(3):633–45. doi:10.22190/FUME210317054L

6. Xue RJ, Liu FJ. A Fractional model and its application to heat prevention coating with cocoon-like hierarchy. *Therm Sci* (2022) 26(3):2493–8. doi:10.2298/TSCI2203493X

7. Guo JG, Zhou LJ, Zhao YP. Instability analysis of torsional MEMS/NEMS actuators under capillary force. *J Colloid Interf Sci* (2009) 331(2):458–62. doi:10.1016/j.jcis.2008.11.069

8. He CH. A variational principle for a fractal nano/microelectromechanical (N/MEMS) system. *Int J Numer Method H* (2023) 33(1):351–9. doi:10.1108/HFF-03-2022-0191

9. Li C, Liu K, Liu H, Yang B, Hu X. Capillary driven electrokinetic generator for environmental energy harvesting. *Mater Res Bull* (2017) 90:81–6. doi:10.1016/j.materresbull.2017.02.022

10. He CH, Amer TS, Tian D, Abolila AF, Galal AA. Controlling the kinematics of a spring-pendulum system using an energy harvesting device. *J Low Freq N A* (2022) 41(3):1234–57. doi:10.1177/14613484221077474

11. Jamali A, Mendes J, Nagaratnam B, Lim M. A new four stage model of capillary pressure in early age concrete: Insights from high capacity tensiometers. *Cement Concrete Res* (2022) 161:106955–67. doi:10.1016/j.cemconres.2022.106955

12. He CH, Liu C. Fractal dimensions of a porous concrete and its effect on the concrete's strength. *Facta Univ-ser Mech* (2023) 21(1):137–50. doi:10.22190/FUME221215005H

13. He CH, Liu C, He JH, SedighiShokri HMA, Gepreel KA. A fractal model for the internal temperature response of a porous concrete. *Appl Comput Math-bak* (2022) 21(1):71–7. doi:10.30546/1683-6154.21.1.2022.71

14. Xiao QH, Wu Z, Qiu JS, Dong ZY, Shi SS. Capillary water absorption performance and damage constitutive model of recycled concrete under freeze-thaw action. *Constr Build Mater* (2022) 353(24):129120–0. doi:10.1016/j.conbuildmat.2022.129120

15. Han CY, He JH. Effect of fabric surface's cleanliness on its moisture/air permeability. *Therm Sci* (2021) 25(2):1517–21. doi:10.2298/TSCI2102517H

16. Xiao JF, Liu X, Luo YM, Cai JC, Xu JF. Oscillations of free surface at the edge of short capillary tubes. *Colloid Surf A* (2020) 591:124572. doi:10.1016/j.colsurfa.2020.124572

17. Saxena RK. Studies on water vapour transfer through nylon and cotton fabrics. *Indian J Fibre Text* (1999) 24(3):188–92.

18. Midha V, Kumar SS, Kumar MN. Investigation on permeability and moisture management properties of different denim fabrics after repeated laundering. *Indian J Fibre Text* (2017) 108(1):71–7. doi:10.1080/00405000.2016.1153873

19. Ha M, Tokura H, Yanai Y, Moriyama T, Tsuchiya N. Combined effects of fabric air permeability and moisture absorption on clothing microclimate and subjective sensation during intermittent exercise at 27 degrees C. *Ergonomics* (1999) 42(7):964–79. doi:10.1080/001401399185243

20. Raja D, Babu VR, Senthilkumar M, Ramakrishnan G, Kannan N. A dynamic sweat transfer tester for analyzing transverse sweat transfer properties of multi-weave structure fabrics. *J Ind Tex* (2014) 44(2):211–31. doi:10.1177/1528083713481836

21. Guan MH, Annaheim S, Camenzind M, Li J, Mandal S, Psikuta A, et al. Moisture transfer of the clothing-human body system during continuous sweating under radiant heat. *Text Res J* (2019) 89(21):4537–53. doi:10.1177/0040517519835767

22. Liu TQ, Yan WT, Yang X, Wang SF. Thermal performance of wickless and orientation independent thin vapor chambers with wettability patterned micro structure. *Therm Sci* (2022) 26(5):4391–400. doi:10.2298/TSCI211106017L

23. Tian D, Li XX, He JH. Geometrical potential and nanofiber membrane's highly selective adsorption property. *Adsorpt Sci Technol* (2019) 37(5-6):367–88. doi:10.1177/0263617418813826

24. Anjum N, He JH, He CH, Ashiq A. A brief review on the asymptotic methods for the periodic behaviour of microelectromechanical systems. *J Appl Comput Mech* (2022) 8(3):1120–40. doi:10.22055/jacm.2022.39404.3401

25. Anjum N, Rahman JU, He JH, Alam MN, Suleman M. An efficient analytical approach for the periodicity of nano/microelectromechanical systems' oscillators. *Math Probl Eng* (2022) 2022:1–12. doi:10.1155/2022/9712199

26. Shokravi M. Dynamic pull-in and pull-out analysis of viscoelastic nanoplates under electrostatic and casimir forces via sinusoidal shear deformation theory. *J Microelectron Reliab* (2017) 71(4):17–28. doi:10.1016/j.microrel.2017.02.006

27. Fan J, Zhang YR, Liu Y, Wang WH, Cao FY, Yang QQ, et al. Explanation of the cell orientation in a nanofiber membrane by the geometric potential theory. *Result Phys* (2019) 15:102537–41. doi:10.1016/j.rinp.2019.102537

28. Yalcinkaya F, Yalcinkaya B, Hruza J, Hrabak P. Effect of nanofibrous membrane structures on the treatment of wastewater microfiltration. *Sci Adv Mater* (2017) 9(5):747–57. doi:10.1166/sam.2017.3027

29. Liu LG, Liu YQ, Li YY, Shen Y, He JH. Dropping in electrospinning process: A general strategy for fabrication of microspheres. *Therm Sci* (2021) 25(2):1295–303. doi:10.2298/TSCI191228025L

30. He JH, Amer TS, Elnaggar S, Galal AA. Periodic property and instability of a rotating pendulum system. *Axioms* (2021) 10(3):191–206. doi:10.3390/axioms10030191

31. He CH, Tian D, Moatimid GM, Salman HF, Zekry MH. Hybrid Rayleigh–van der pol–duffing oscillator: Stability analysis and controller. *J Low Freq N A* (2022) 41(1): 244–68. doi:10.1177/14613484211026407

32. He JH. The simplest approach to nonlinear oscillators. *Results Phys* (2019) 15: 102546–8. doi:10.1016/j.rinp.2019.102546

33. He JH. The simpler, the better: Analytical methods for nonlinear oscillators and fractional oscillators. *J Low Freq N A* (2019) 38(3-4):1252–60. doi:10.1177/1461348419844145

34. Feng GQ, Niu JY. An analytical solution of the fractal toda oscillator. *Results Phys* (2023) 44:106208–15. doi:10.1016/j.rinp.2023.106208

35. Elias-Zuniga A, Palacios-Pineda LM, Jimenez-Cedeno IH, Martinez-Romero O, Trejo DO. He's frequency-amplitude formulation for nonlinear oscillators using Jacobi elliptic functions. *J Low Freq N A* (2020) 39(4):þ1216–23. doi:10.1177/1461348420972820

36. He CH, Liu C. A modified frequency-amplitude formulation for fractal vibration systems. *Fractals* (2022) 30(3):2250046–8. doi:10.1142/S0218348X22500463

37. He CH, El-Dib YO. A heuristic review on the homotopy perturbation method for non-conservative oscillators. *J Low Freq N A* (2021) 41(2):572–603. doi:10.1177/14613484211059264

38. He JH, He CH, Alsolami AA. A good initial guess for approximating nonlinear oscillators by the homotopy perturbation method. *Facta Univ-ser Mech* (2023) 21(1): 021–9. doi:10.22190/FUME230108006H

39. Wang SQ, He JH. Variational iteration method for solving integro-differential equations. *Phys Lett A* (2007) 367(3):188–91. doi:10.1016/j.physleta.2007.02.049

40. Wang SQ. A variational approach to nonlinear two-point boundary value problems. *Comput Math Appl* (2009) 58(11):2452–5. doi:10.1016/j.camwa.2009.03.050

41. Chen HW, Zhang PF, Zhang LW, Iu HLL, Jiang Y, Zhang DY, et al. Continuous directional water transport on the peristome surface of nepenthes alata. *Nature* (2016) 532:85–9. doi:10.1038/nature17189