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THERMAL OSCILLATION ARISING IN A HEAT SHOCK OF A POROUS HIERARCHY AND ITS APPLICATION

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Abstract. *A building or a bridge might collapse after a heat shock. This paper shows that a porous hierarchy of a coating can effectively prevent a building or a bridge from such damage. A cocoon's geometrical structure is studied and its resistance to the heat shock is revealed by a thermal oscillator. The theoretical model reveals an extremely low frequency of the thermal oscillator, which is very important for cocoons' biomechanism, especially in the heat insulation function. At the same time, it shows that the cocoons have the best thickness to protect the pupa from the environment. In addition, surface temperature measurement of hierarchical mulberry leaves is performed. This work provides new insights into biomimetic design of the protective building and coatings.*

Key Words: *Silkworm Cocoon, Hierarchical Structure, Heat Conduction, Microporous Capillary, Thermal Oscillation, Freeze-thaw Damage*

1. INTRODUCTION

A building under a sudden heat shock will suffer a great damage as we can see from the September 11, 2001, attacks on the World Trade Center, New York, often referred to as 9/11; the high buildings of the World Trade Center collapsed after the attack. The huge energy was transferred to the metal structure of the building, and the temperature was too high to support the building. It is extremely important to protect a building from the heat shock with a high environment temperature. The general thermal insulation is impossible for heat shock presentation. It seems there is no approach to preventing such damage so far.

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This paper aims at a new idea for this purpose inspired from a silkworm cocoon, which is generally considered to protect the pupa from predators and hazards. Actually, it can also prevent a sudden heat shock. Liu et al. [1] proposed the fractal model for heat transfer in hierarchic cocoons for the first time to explain the fascinating phenomenon of pupa survival under extreme environment. He's fractional derivative was adopted to study the heat conduction in cocoons which are regarded as fractal medium [2]. Moreover, Liu et al. [3] defined a new fractional derivative through the variational iteration method and applied it to explain the outstanding thermal protection of insulation clothing with cocoon-like porous structure. Because the cocoon is extremely insensitive to environment change and a pupa can survive in a harsh environment, a mathematical explanation to this superior survival ability and an experiment have been carefully carried out to verify the mechanism [4]. These research studies are of great importance for the biomimetic design of functional materials in various fields.

A very thin and lightweight cocoon wall has a distinctive hierarchical structure and multiple functions [5-7]; the pupa can suffer from a sudden temperature change in some extreme weather situations, and the cocoon wall plays a critical role in protecting the pupa from energy loss and a sudden heat shock. The hierarchical porous structure of the cocoon wall gives the silkworm pupa unexpected properties, such as energy protection and the heat shock protection. However, a paucity of literature reported about its mechanism of thermal performance, especially a heat shock in the cocoon wall. Much literature revealed that a low frequency property of some vibration systems plays an important role in various applications. He, Liu and Gepreel found that the low frequency property of a porous concrete beam can prevent vibration damage [8]; He, Kou, et al. revealed all vibrations in a porous medium have a low frequency property when time tends to infinity [9]; Zuo applies the low frequency property of a fractal-like spring system to 3D printing technology [10-12]; He and El-Dib studied the frequency property of a fractional Kundu–Mukherjee–Naskar equation [13]. He and his colleagues revealed a long-lost technology to collect water from air by the low frequency theory [14, 15].

The capillary effect is also important in the heat and mass transfer [16, 17]. Jin et al. [18] studied the low frequency property of a capillary vibration. Lin et al. [19, 20] established a model for a release oscillation in a hollow fiber, and ions release depends upon the low frequency property.

In this work, we will study the geometric structure of the silkworm cocoon and analyze its thermal conduction properties and design a porous coating of the building wall which can prevent from a sudden heat shock.

2. GEOMETRIC ANALYSIS OF THE SILKWORM COCOON

The cocoon wall structure is considered as a porous medium consisting of randomly arranged continuous silk fibers. Each layer images of the silkworm cocoon are presented in Fig. 1. From the SEM micrographs, they reveal that the silkworm cocoons have multilayer and porous structures with double silk fibroin fibers covered by sericin. The morphologies of each layer are remarkably different. From the outer to the inner surface, the density and the amount of bonding of fibers increase.

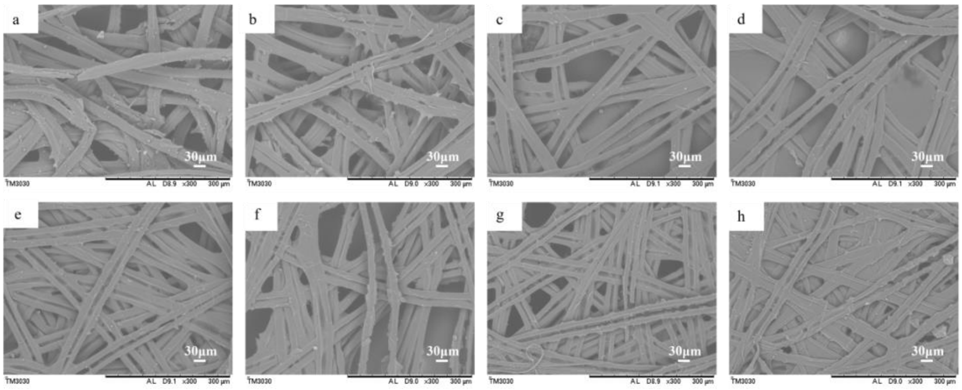

Fig. 1 SEM micrographs of silkworm cocoon layers from outer (a) to inner (h), scale bar: 30 μm

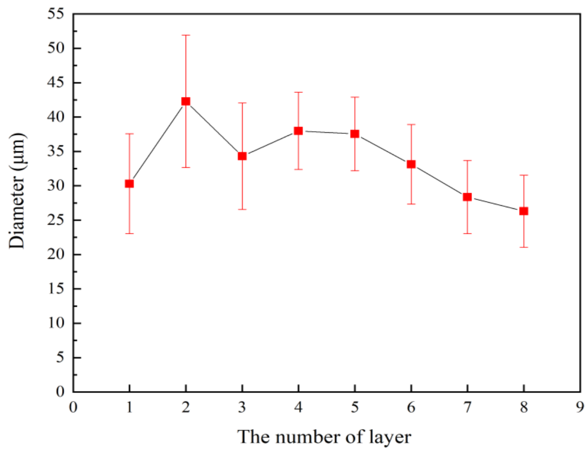

Fig. 2 The average diameters of cocoon silks from outer (1) to inner (8)

The silk's diameter of each layer was also measured (Fig. 2). It is found that the average diameter of the silk gradually decreases from the outer layer to the inner layer (30.3, 42.3, 34.3, 38, 37.5,33.1, 28.3 and 26.3 μm). In addition, the diameter of the outermost fibers is smaller, which may be due to the component loss caused by the exposure to air. This further illustrates that the cocoon has a unique hierarchical structure.

3. The Silkworm Cocoon Under a Sudden Heat Shock

A sudden heat shock will greatly affect a building's reliability and life. The freeze-thaw damage is the main reason of the failure of a cement-based material [21-29]. If the thermal response to the environment temperature change is slow and the inner temperature will not change much with 12 hours, such freeze-thaw damage can be avoided by covering a porous coating with a structure similar to the cocoon wall.

In many cases, a sudden heat shock also refers to a sudden increase or decrease of temperature in harsh environments [30]. In order to cope with this problem, phase change materials (PCM) are widely used in thermal energy systems [31-33]. The main feature of PCM is latent heat storage, which has higher storage density than conventional sensible heat storage due to a high enthalpy change in the phase change process. The latent heat storage based on PCM can be applied in various fields, such as solar heat storage, energy-saving buildings and waste heat recycle, etc [34-37]. However, there always exist diverse defects, such as phase separation, low heat transfer rate, supercooling, leakage in the molten state, instability of performance [38]. Especially the buildings on fire, which use phase change materials, will be a very dangerous heat source due to a low heat transfer rate of PCM. This brings great difficulties to firefighters' rescue operations, such as taking longer time to put out the fire, and may even sacrifice more people [39]. Hence, thermal conductivity enhancement is one of the main issues for the PCM in the application field of the latent heat storage. In the same way, if the phase change materials are added to the fire suit, the heat cannot be conducted in time, which will directly threaten the lives of firefighters. What we need is a porous hierarchical structure that can not only store heat and keep warm, but also conduct heat in time. The closer it is to the room or the human body, the slower the conduction will be. Moreover, people will not feel the discomfort caused by a sudden heat shock. Therefore, thermal conductivities of the silkworm cocoon are studied in this paper. The silkworm cocoons are expected to have unique characteristics under a sudden heat shock.

Thermal conductivities of the silkworm cocoon were carried out using Temp.& Hum. Chamber T/C1000-70. The temperature rise (from the initial conditions of 26 ℃ to 57 ℃) and fall (from 49℃ to 20℃) profiles are obtained and shown in Figs. 3 and 4, respectively.

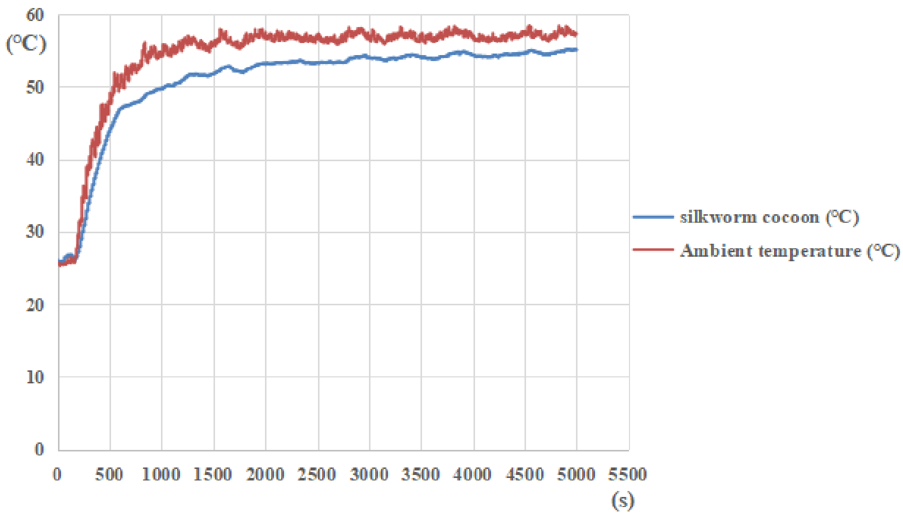

Fig. 3 Temperature profiles for internal of the silkworm cocoon as the ambient temperature increases

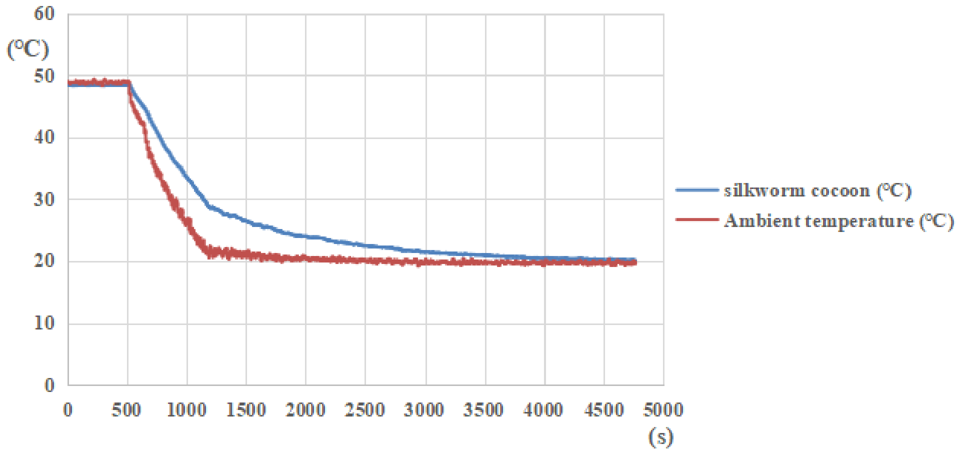

Fig. 4 Temperature profiles for internal of the silkworm cocoon as the ambient temperature decreases

It can be observed that the temperature inside the silkworm cocoon changes slowly when the ambient temperature change occurs, which indicates that the cocoon has a certain degree of temperature buffering. The internal temperature of the cocoon tends to be close to the surrounding temperature, but the internal temperature will not change immediately when the cocoons encounter a sudden temperature change. Therefore, we expect that it may be closely related to the heat flow transfer and the unique porous hierarchical structure of the silkworm cocoon.

4. Thermal Oscillation and its Low Frequency Property

There are many kinds of thermal oscillations. Especially, the flow boiling instabilities are undesired phenomena which may cause a premature critical heat flux (CHF), high pressure drops, control and operational problems and mechanical vibrations of the system components [40, 41]. Chávez et al. studied thermal oscillations during flow boiling of hydrocarbon refrigerants in a microchannels array heat sink [42]. Megahed [43] has verified the effect of mass velocity variation on thermal oscillations. Recently, Kuang et al. [44] found that as the saturation temperature increased, the frequency of the thermal oscillations increased. In general, the frequency and amplitude of the oscillations increase with increasing heat flux. This behavior is due to the intensification of the boiling forces [45]. In addition, Kim et al. [46] have investigated the rapid thermal oscillatory flow in an asymmetric micro pulsating heat exchanger (MPHE) and Demir et al. [47] have studied the dynamics of the bacterial flagellar motor’s angular velocity in response to thermal oscillations while focusing on the effect of frequency.

Cell growth on nanofibers can be explained by thermal oscillations. Fan et al. [48] showed that the capillary-like force which is parallel to the fiber orientation have a good guide for cell orientation. The geometric potential becomes weak when the distance between two adjacent fibers becomes wide. Cell orientation can also be guided by the boundary-induced force induced by adjacent nanofibers. Besides, Lin et al. [19, 20, 49] studied the release oscillation in a hollow fiber and established a fractional model. The results showed that the ions release depends upon the low frequency property.

Cocoon is a hierarchical porous medium. In this paper, we approximate the porosity in the cocoon wall as a microporous capillary channel for heat transfer. The model schematic is illustrated in Fig. 5. Heat flow is slowly transferred from the outer layer to the inner layer.

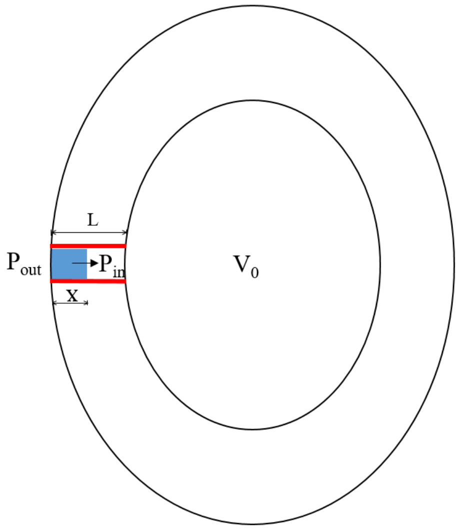

Fig. 5 Schematic of heat transfer in a microporous capillary channel (marked by red lines)

For a microporous capillary channel, the Newton's second law for thermal oscillations can be written in the form

$$F = m\ddot{x} \tag{1}$$

where x is removal from the equilibrium position, m is the total hot air mass in a microporous capillary channel and F is the force caused by the air pressure difference between the inside and outside the cocoon.

Force F can be expressed as

$$F = \left(P_{out} - P_{in}\right)A \tag{2}$$

where P_{out} and P_{in} are the hot air pressure outside the cocoon and the air pressure inside the cocoon, respectively. A is a cross-sectional area of the microporous capillary channel.

Combining Eqs. (1) and (2), we have

$$\boldsymbol{\rho} Ax\ddot{x} - \left(P_{out} - P_{in}\right)A = 0 \tag{3}$$

where $\boldsymbol{\rho}$ is hot air density.

According to the state equation of gas

$$PV = nRT \tag{4}$$

where P is pressure, V is volume, n is moles of gas, R is the thermodynamic constant and T is temperature.

Air pressure P_{in} in the cocoon can be written

$$P_{in} = \frac{n_{in}RT_{in}}{V_0 + (L-x)A} \tag{5}$$

where R is gas constant, V_0 is the inner volume of the cocoon (shown in Fig. 5), T_{in} is the internal temperature of the cocoon and L is the cocoon thickness.

Substituting Eq. (5) into Eq. (3), we get

$$\rho A x \ddot{x} - P_{out}A + \frac{n_{in}RT_{in}}{V_0 + (L-x)A} = 0 \tag{6}$$

After the deformation of Eq. (6), it shows

$$\ddot{x} + \frac{1}{\rho A x}\frac{n_{in}RT_{in}}{V_0 + (L-x)A} - \frac{P_{out}}{\rho x} = 0 \tag{7}$$

The initial conditions are

$$x(0) = L_0 \qquad \dot{x}(0) = 0 \tag{8}$$

The nonlinear equation given in Eq. (7) with initial conditions given in Eq. (8) can be solved by the homotopy perturbation method [13, 15, 50-52] or by the variational iteration method [53-56], or He's frequency formulation [57-60]. Hereby the Taylor series method [61-63] is adopted.

After a simple transformation, we obtain the equation:

$$\ddot{x}(0) = \frac{P_{out}A\left[V_0 + (L-L_0)A\right] - n_{in}RT_{in}}{\rho A L_0\left[V_0 + (L-L_0)A\right]} \tag{9}$$

The Taylor series solution to second order is

$$x(t) = x(0) + \dot{x}(0)t + \frac{\ddot{x}(0)}{2!}t^2 + \ldots = L_0 + \frac{P_{out}A\left[V_0 + (L-L_0)A\right] - n_{in}RT_{in}}{2\rho A L_0\left[V_0 + (L-L_0)A\right]}t^2 \tag{10}$$

According to the oscillation property, we can obtain

$$x\left(T_p/4\right) = L_0 + \frac{P_{out}A\left[V_0 + (L-L_0)A\right] - n_{in}RT_{in}}{2\rho A L_0\left[V_0 + (L-L_0)A\right]}\left(\frac{T_p}{4}\right)^2 = 0 \tag{11}$$

where T_p is considered the period of the heat flow vibration.

From Eq. (11), the solution is shown as

$$T_P = 4L_0 \sqrt{\frac{2\rho A\left[\left(L_0 - L\right)A - V_0\right]}{P_{out}A\left[V_0 + \left(L - L_0\right)A\right] - n_{in}RT_{in}}} \tag{12}$$

The frequency of heat flow oscillation is

$$w = \frac{2\pi}{T_p} = \frac{\pi}{2L_0 \sqrt{\frac{2\rho A\left[\left(L_0 - L\right)A - V_0\right]}{P_{out}A\left[V_0 + \left(L - L_0\right)A\right] - n_{in}RT_{in}}}} \tag{13}$$

Eq. (13) roughly describes the main factors which affect the frequency of heat flow vibration.

The low frequency property is very important for cocoons. It implies the heat cannot be transferred to a long distance, so that the pupa will not be affected by the heat shock outside. In order to ensure that the frequency is small, it can be seen from Eq. (13)

$$P_{out}A\left[V_0 + \left(L - L_0\right)A\right] - n_{in}RT_{in} << 1 \tag{14}$$

In other words, Eq. (14) is equivalent to

$$P_{out}A\left[V_0 + \left(L - L_0\right)A\right] - n_{in}RT_{in} = 0 \tag{15}$$

After transformation, we have

$$L_0 = L - \frac{1}{A}\left(\frac{n_{in}RT_{in}}{P_{out}A} - V_0\right) \tag{16}$$

L_0 represents amplitude and $L_0 \to 0$. Eq. (16) becomes

$$L = \frac{1}{A}\left(\frac{n_{in}RT_{in}}{P_{out}A} - V_0\right) \tag{17}$$

Take the derivative of *1/A*

$$\frac{dL}{d\left(1/A\right)} = 0 \tag{18}$$

That is

$$\frac{2n_{in}RT_{in}}{P_{out}A} - V_0 = 0 \tag{19}$$

The optimal pore size can be obtained

$$A_{opt} = \frac{2n_{in}RT_{in}}{P_{out}V_0} \tag{20}$$

According to the state equation,

$$\frac{P}{\rho} = RT \tag{21}$$

A higher temperature results in a larger pressure (P_{out}), and the porous size should be smaller, so the last cascade of the porous hierarchy of the coating can consist of nanofibers [64].

5. Application in A Building Exterior Wall

Porous structure with cocoon-like hierarchy has good thermal insulation performance. This kind of structure can play a very good thermal buffer effect when used in building exterior wall coating. The schematic of thermal buffer in hierarchical porous structure is shown in Fig. 6. When a sudden heat shock from the external environment reaches the exterior wall coating and passes through the hierarchical porous structure, the temperature changes from fast to slow. The closer to the exterior wall, the extremely slow the temperature change is. Finally, the temperature slowly reaches the room temperature.

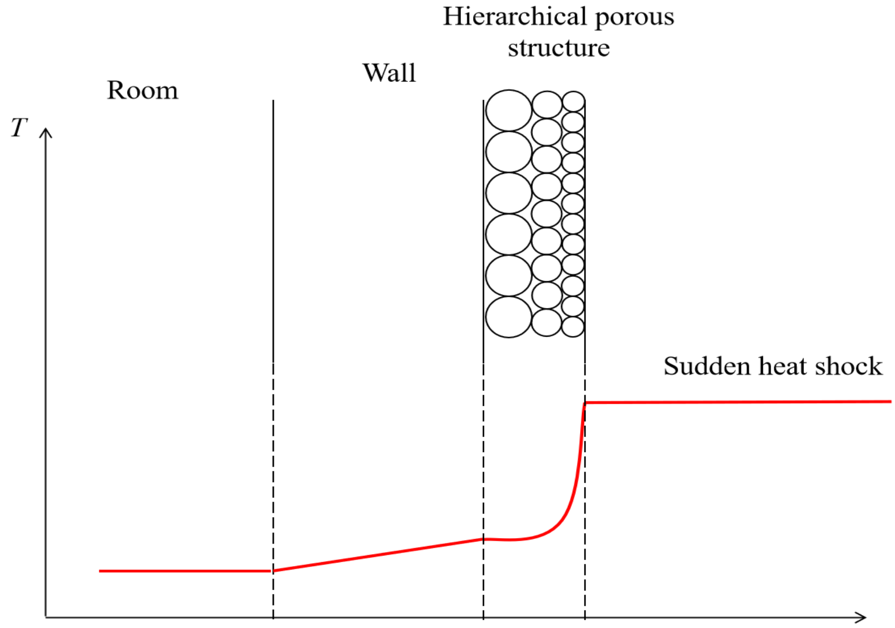

Fig. 6 Schematic of thermal buffer in hierarchical porous structure

Leaves have a common hierarchical structure in nature [65-67]. They endure the alternation of temperature difference between day and night. This experiment was to measure the temperature of the upper and lower surfaces of a mulberry leaf every half an hour in the Soochow University campus. It was sunny, and the weather favored the measurements. Fig. 7 shows the temporal evolution of the leaf surface temperatures from 9:30 a.m. to 3:30 p.m., where the upper and the lower temperatures were marked with the blue and green colors, respectively, and the environment temperature was marked with the red one. The average value of surface temperatures of the mulberry leaf was used in our experiment. It can be seen from Fig. 7 that the ambient temperature increases gradually; it reaches the maximum at 2:00 p.m. and then it tends to be stable. Due to the sunlight, the temperatures of the upper and lower surfaces of the mulberry leaf change slightly with the rise of the ambient temperature, and both the cases have seen an obvious oscillation in temperature with different frequencies. The upper surface has a higher frequency of the thermal oscillation than the lower one. A higher frequency results in a higher metabolic rate, and it can inspire the specially needed permeability design for cloth and house walls.

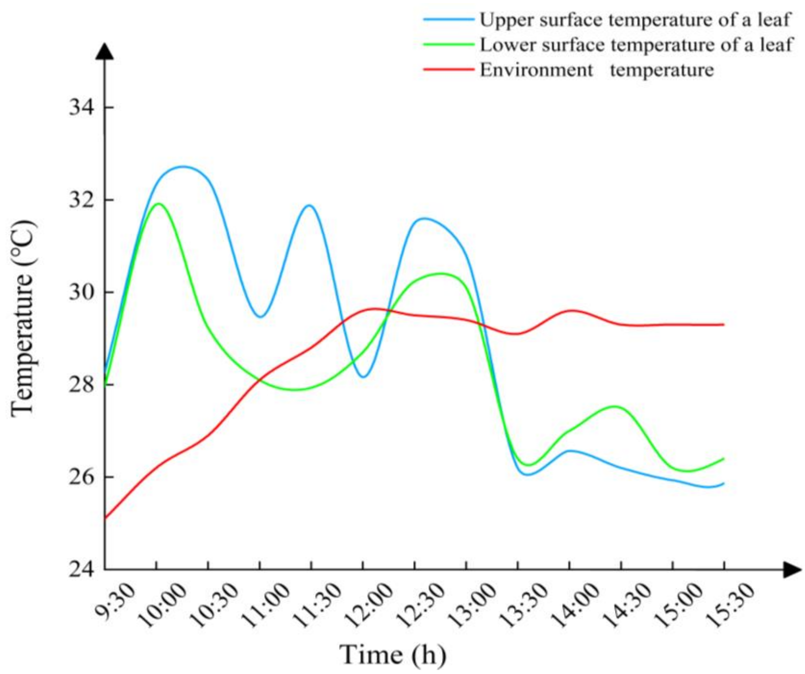

Fig. 7 The temporal evolution of upper and lower surface temperatures of a mulberry leaf

6. CONCLUSIONS

The cocoon wall plays a very good role in protecting silkworm pupae, no matter how the environment changes. The heat flow in the microporous capillary channel moves extremely slowly from the outer layer to the inner layer of the cocoon. It is precisely because of the super slow energy transmission through the cocoon wall that the silkworm pupae will not suffer damage due to either excessively high or low temperatures. The cocoons have a good heat preservation function and the optimal pore size (Eq. (20)), which is inversely proportional to cocoon volume.

In this paper, SEM elucidated the geometric structure of silkworm cocoons, and thermal conduction experiments were carried out to reveal the excellent thermal prevention properties. Especially, we obtained the frequency of thermal oscillation and analyzed the main influence factors. This work will lay a solid foundation for biomimetic design of the protective clothing and coatings in extreme environment conditions. Next, we will discuss the relationship between the heat transfer frequency and the fractal dimensions of the cocoon wall, which is going on in our laboratory.

REFERENCES

1. Fei, D.D., Liu, F.J., Cui, Q.N., He, J., 2013, *Fractal approach to heat transfer in silkworm cocoon hierarchy*, Thermal Science, 17(5), pp. 1546-1548.
2. Liu, F.J., Li, Z.B., Zhang, S., Liu, H.Y., 2015, *He's fractional derivative for heat conduction in a fractal medium arising in silkworm cocoon hierarchy*, Thermal Science, 19(4), pp. 1155-1159.
3. Liu, F.J., Wang, P., Zhang, Y., Liu, H.Y., He, J., 2016, *A fractional model for insulation clothings with cocoon-like porous structure*, Thermal Science, 20(3), pp. 779-784.
4. Liu, F.J., Liu, H.Y., Li, Z.B., He, J., 2017, *A delayed fractional model for cocoon heat-proof property*, Thermal Science, 21(4), pp. 1867-1871.
5. Tao, H., Kaplan, D.L., Omenetto, F.G., 2012, *Silk materials—a road to sustainable high technology*, Advanced Materials, 24(21), pp. 2824-2837.
6. Wegst, U.G.K., Bai, H., Saiz, E., Tomsia, A.P., Ritchie, R.O., 2015, *Bioinspired structural materials*, Nature Materials, 14(1), pp. 23–36.
7. Omenetto, F.G., Kaplan, D.L., 2010, *New opportunities for an ancient material*, Science, 329(5991), pp. 528–531.
8. He, C.H., Liu, C., Gepreel, K.A., 2021, *Low frequency property of a fractal vibration model for a concrete beam*, Fractals, doi: 10.1142/S0218348X21501176.
9. He, J.H., Kou, S.J., He, C.H., Zhang, Z.W., Gepreel, K.A., 2021, *Fractal oscillation and its frequency-amplitude property*, Fractals, doi: 10.1142/S0218348X2150105X.
10. Zuo, Y.T., 2021, *A gecko-like fractal receptor of a three-dimensional printing technology: a fractal oscillator*, Journal of Mathematical Chemistry, doi: 10.1007/s10910-021-01212-y.
11. Zuo, Y.T., Liu, H.J., 2021, *A fractal rheological model for sic paste using a fractal derivative*, Journal of Applied and Computational Mechanics, 7, pp. 13-18.
12. Zuo, Y.T., Liu, H.J., 2021, *Fractal approach to mechanical and electrical properties of graphene/sic composites*, Facta Universitatis-Series Mechanical Engineering, doi: 10.22190/FUME201212003Z.
13. He, J.H., El-Dib, Y.O., 2020, *Periodic property of the time-fractional Kundu–Mukherjee–Naskar equation*, Results in Physics, 19, pp. 1-6.
14. He, C.H., He, J., Sedighi, H.M., 2020, *Fangzhu((sic)(sic)): an ancient Chinese nanotechnology for water collection from air: history, mathematical insight, promises and challenges*, Mathematical Methods in the Applied Sciences, DOI: 10.1002/mma.6384.
15. He, J.H., El-Dib, Y.O., 2020, *Homotopy perturbation method for Fangzhu oscillator*, Journal of Mathematical Chemistry, 58(10), pp. 2245-2253.
16. Han, C., He, J., 2021, *Effect of fabric surface's cleanliness on its moisture/air permeability*, Thermal Science, 25, pp. 1517-1521.
17. He, J.H., Jin, X., 2020, *A short review on analytical methods for the capillary oscillator in a nanoscale deformable tube*, Mathematical Methods in the Applied Science, https://doi.org/10.1002/mma.6321.
18. Jin, X., Liu, M.N., Pan, F., Li, Y.P., Fan, J., 2019, *Low frequency of a deforming capillary vibration, part 1: mathematical model*, Journal of Low Frequency Noise Vibration and Active Control, 38(3-4), pp. 1676-1680.
19. Lin, L., Yao, S.W., 2019, *Release oscillation in a hollow fiber – part 1: mathematical model and fast estimation of its frequency*, Journal of Low Frequency Noise Vibration and Active Control, 38(3-4), pp. 1703-1707.

20. Lin, L., Li, H.G., Yao, S.W., 2019, *Experimental verification of the fractional model for silver ion release from hollow fibers*, Journal of Low Frequency Noise Vibration and Active Control, 38(3-4), pp. 1041-1044.
21. Rhardane, A., Sleiman, S. A., Alam, S.Y., Grondin, F., 2021, *A quantitative assessment of the parameters involved in the freeze-thaw damage of cement-based materials through numerical modelling*, Construction and Building Materials, 272, 121838.
22. Wang, Y., Gao, S.H., Li, C.H., Han, J.Q., 2021, *Energy dissipation and damage evolution for dynamic fracture of marble subjected to freeze-thaw and multiple level compressive fatigue loading*, International Journal of Fatigue, 142, 105927.
23. Zhang, Z.Y., Liu, Q., Wu, Q., Xu, H.N., Liu, P.F., Oeser, M., 2021, *Damage evolution of asphalt mixture under freeze-thaw cyclic loading from a mechanical perspective*, International Journal of Fatigue, 142, 105923.
24. Tu, Y.M., Liu, D.Y., Wang, T.F., Yuan, L., 2021, *Evaluation on later-age performance of concrete subjected to early-age freeze-thaw damage*, Construction and Building Materials, 270, 121491.
25. Abedi, M., Torshizi, S.E.M., Sarfaraz, R., 2021, *Damage mechanisms in glass/epoxy composites subjected to simultaneous humidity and freeze-thaw cycles*, Engineering Failure Analysis, 120, 105041.
26. Deng, X.H., Gao, X.Y., Wang, R., Gao, M.X., Yan, X.X., Cao, W.P., Liu, J.T., 2021, *Investigation of microstructural damage in air-entrained recycled concrete under a freeze-thaw environment*, Construction and Building Materials, 268, 121219.
27. Lu, C.F., Zhou, Q.S., Wang, W., Wei, S.H., Wang, C., 2021, *Freeze-thaw resistance of recycled aggregate concrete damaged by simulated acid rain*, Journal of cleaner production, 280(1), 124396.
28. Feng, Z.J., Huo, J.W., Hu, H.B., Zhao, R.X., Wang, F.C., Jiang, G., Yao, X.H., Li, T., Song, Z.Y., 2021, *Research on Corrosion Damage and Bearing Characteristics of Bridge Pile Foundation Concrete under a Dry-Wet-Freeze-Thaw Cycle*, Advances in Civil Engineering, 2021, 8884396.
29. Yang, X.R., Jiang, A.N., Zhang, F.R., 2021, *Research on creep characteristics and variable parameter-based creep damage constitutive model of gneiss subjected to freeze-thaw cycles*, Environmental Earth Sciences, 80(1), 7.
30. Lagerspetz, K.Y.H., 2003, *Thermal acclimation without heat shock, and motor responses to a sudden temperature change in Asellus aquaticus*, Journal of Thermal Biology, 28(5), pp. 421-427.
31. Faraj, K., Khaled,M., Faraj, J., Hachem, F., Castelain, C., 2020, *Phase change material thermal energy storage systems for cooling*, Renewable and Sustainable Energy Reviews, 119, 109579.
32. Da Cunha, S.R.L., De Aguiar, J.L.B., 2020, *Phase change materials and energy efficiency of buildings: A review of knowledge*, Journal of Energy Storage, 27, 101083.
33. Wu, S.F., Yan, T., Kuai, Z.H., Pan, W.G., 2020, *Thermal conductivity enhancement on phase change materials for thermal energy storage: A review*, Energy Storage Materials, 25, pp. 251-295.
34. Xiao, Q., Yuan, W., Li, L., Xu, T., 2018, *Fabrication and characteristics of composite phase change material based on Ba(OH)(2)·8H(2)O for thermal energy storage*, Solar Energy Materials and Solar Cells, 179, pp. 339–345.
35. Gao, H., Wang, J., Chen, X., Wang, G., Huang, X., Li, A., 2018, *Nanoconfinement effects on thermal properties of nanoporous shape-stabilized composite PCMs: A review*, Nano Energy, 53, pp. 769–797.
36. Huang, X., Chen, X., Li, A., Atinafu, D., Gao, H., Dong, W., 2019, *Shape-stabilized phase change materials based on porous supports for thermal energy storage applications*, Chemical Engineering Journal, 356, pp. 641–661.
37. Agyenim, F., Hewitt, N., Eames, P., Smyth, M., 2010, *A review of materials, heat transfer and phase change problem formulation for latent heat thermal energy storage systems (LHTESS)*, Renewable & Sustainable Energy Reviews, 14(2), pp. 615–628.
38. Lin, Y., Jia, Y., Alva, G., Fang, G., 2018, *Review on thermal conductivity enhancement, thermal properties and applications of phase change materials in thermal energy storage*, Renewable & Sustainable Energy Reviews, 82(3), pp. 2730–2742.
39. Song, G., Ma, S., Tang, G., Yin, Z., Wang, X., 2010, *Preparation and characterization of flame-retardant form-stable phase change materials composed by EPDM, paraffin and nano magnesium hydroxide*, Energy, 35(5), pp. 2179–2183.
40. Bon, B., Kakac, S., 2008, *A review of two-phase flow instability dynamic instabilities in tube boiling systems*, International Journal of Heat and Mass Transfer, 51(3-4), pp. 399-433.
41. Kakac, S., Veziroglu, T.N., Padki, M.M., Fu, L.Q., Chen, X.J., 1990, *Investigation of thermal instabilities in a forced convection upward boiling system*, Experimental Thermal and Fluid Science, 3(2), pp. 191-201.
42. Chávez, G.A., Moraga, N.O., Ribatski, G., 2019, *Thermal oscillations during flow boiling of hydrocarbon refrigerants in a microchannels array heat sink*, Applied Thermal Engineering, 157, 113725.

43. Megahed, A., 2011, *Experimental investigation of flow boiling characteristics in a cross-linked microchannel heat sink*, International Journal of Multiphase Flow, 37(4), pp. 380-393.
44. Kuang, Y.W., Wang, W., Miao, J.Y., Yu, X.G., Zhang, H.X., Zhuan, R., 2017, *Flow boiling of ammonia and flow instabilities in mini-channels*, Applied Thermal Engineering, 113, pp. 831-842.
45. Prajapati, Y.K., Pathak, M., Khan, M.K., 2017, *Bubble dynamics and flow boiling characteristics in three different microchannel configurations*, International Journal of Thermal Science, 112, pp. 371-382.
46. Kim, Y.B., Song, H.W., Sung, J., 2018, *Flow behavior of rapid thermal oscillation inside an asymmetric micro pulsating heat exchanger*, 120, International Journal of Heat and Mass Transfer, pp. 923-929.
47. Demir, M., Salman, H., 2017, *Resonance in the response of the bacterial flagellar-motor to thermal oscillations*, Physical Review E, 95(2), 022419.
48. Fan, J., Zhang, Y.R., Liu, Y., Wang, Y.H., Cao, F.Y., Yang, Q.Q., Tian, F.M., 2019, *Explanation of the cell orientation in a nanofiber membrane by the geometric potential theory*, Results in Physics, 15, pp. 1-4.
49. Lin, L., Li, H.G., Liu, Y.P., 2019, *Release oscillation in a hollow fiber Part 2: the effect of its frequency on ions release and experimental verification*, Journal of Low Frequency Noise, Vibration and Active Control, doi: 10.1177/1461348419874973.
50. He, J.H., El-Dib, Y.O., 2020, *The reducing rank method to solve third-order duffing equation with the homotopy perturbation*, Numerical Methods for Partial Differential Equations, 37(2), pp. 1800-1808.
51. He, J.H., El-Dib, Y.O., 2021, *Homotopy perturbation method with three expansions*, Journal of Mathematical Chemistry, doi: 10.1007/s10910-021-01237-3.
52. Yu, D.N., He, J., Garcia, A.G., 2019, *Homotopy perturbation method with an auxiliary parameter for nonlinear oscillators*, Journal of Low Frequency Noise Vibration and Active Control, 38(3-4), pp. 1540-1554.
53. He, J.H., 2006, *Some asymptotic methods for strongly nonlinear equations*, International Journal of Modern Physics B, 20(10), pp. 1141–1199.
54. He, J.H., Latifizadeh, H., 2020, *A general numerical algorithm for nonlinear differential equations by the variational iteration method*, International Journal of Numerical Methods for Heat and Fluid Flow, 30(11), pp. 4797-4810.
55. He, J.H., Nurakhmetov, D., Skrzypacz, P., Wei, D.M., 2019, *Dynamic pull-in for micro-electromechanical device with a current-carrying conductor*, Journal of Low Frequency Noise Vibration and Active Control, doi: 10.1177/1461348419847298.
56. He, J.H., Skrzypacz, P.S., Zhang, Y.N., Pang, J., 2020, *Approximate periodic solutions to microelectromechanical system oscillator subject to magnetostatic excitation*, Mathematical Methods in the Applied Sciences, doi: 10.1002/mma.7018.
57. He, J.H., 2019, *The simpler, the better: analytical methods for nonlinear oscillators and fractional oscillators*, Journal of Low Frequency Noise Vibration and Active Control, 38(3-4), pp. 1252-1260.
58. He, J.H., 2019, *The simplest approach to nonlinear oscillators*, Results in Physics, 15, pp. 1-2.
59. He, C.H., Wang, J.H., Yao, S.W., 2019, *A complement to period/frequency estimation of a nonlinear oscillator*, Journal of Low Frequency Noise Vibration and Active Control, 38, pp. 992-995.
60. Qie, N., Hou, W.F., He, J., 2020, *The fastest insight into the large amplitude vibration of a string*, Reports in Mechanical Engineering, 2(1), pp. 1-5.
61. He, J.H., 2020, *Taylor series solution for a third order boundary value problem arising in architectural engineering*, Ain Shams Engineering Journal, 11(4), pp. 1411-1414.
62. He, C.H., Shen, Y., Ji, F.Y., He, J., 2020, *Taylor series solution for fractal bratu-type equation arising in electrospinning process*, Fractals, 28(1), pp. 1-8.
63. He, J.H., 2019, *A simple approach to one-dimensional convection-diffusion equation and its fractional modification for ereaction arising in rotating disk electrodes*, Journal of Electroanalytical Chemistry, 854, pp. 1-2.
64. Liu, L.G., Liu, Y.Q., Li, Y.Y., Shen, Y., He, J., 2021, *Dropping in electrospinning process: a general strategy for fabrication of microspheres*, Thermal Science, doi: 10.2298/TSCI191228025L.
65. Xin, Q.P., Li, X., Hou, H.L., Liang, Q.Q., Guo, J.P., Wang, S.F., Zhang, L., Lin, L.G., Ye, H., Zhang, Y.Z., 2021, *Superhydrophobic Surface-Constructed Membrane Contactor with Hierarchical Lotus-Leaf-Like Interfaces for Efficient SO2 Capture*, ACS Applied Materials & Interfaces, 13(1), pp. 1827-1837.
66. Cheng, S.A., Yu, Z., Lin, Z.F., Li, L.X., Li, Y.H., Mao, Z.Z., 2020, *A lotus leaf like vertical hierarchical solar vapor generator for stable and efficient evaporation of high-salinity brine*, Chemical Engineering Journal, 401, 126108.
67. Chen, L.H., 2020, *Hierarchically porous materials and green chemistry-an interview with Ming-Yuan He*, National Science Review, 7(11), pp. 1759-1761.