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Review of the Characteristic Curves of Silkworm Cocoon Hot air Drying and its Technological Configuration

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Abstract

To pass on Chinese cocoon-drying technology to developing countries, this paper reviews characteristic curves of silkworm cocoon hot air drying and its recent research advances in cocoon-drying technology in China based on the epochal and regional characters of cocoon drying technology development. (1) Three characteristic curves of cocoon drying are systematically explained, each of which can be divided into preheating, constant speed, and deceleration stages. The temperature susceptibility (i.e., the characteristics of response to temperature conditions) curve of the pupa successively shows heating, constant temperature, and heating processes. (2) Changes in the drying speed and temperature susceptibility of a fresh cocoon layer and naked pupae were examined in detail before and after pupae were killed in the preheating stage. It is proposed that heating the cocoons as soon as possible during the preheating stage of cocoon drying improves the work efficiency and cocoon quality. (3) The effects of the temperature and humidity of the hot air on the cocoon drying speed (i.e., speed coefficients) are obtained using the enthalpy psychrometric chart. The parameter configuration of cocoon drying technology is elaborated according to the speed coefficients in combination with the characteristic curves of cocoon drying and the influence of the laws of cocoon drying technology on cocoon quality. Furthermore problems in the technological configuration and the direction of future development are noted.

Key words: *cocoon, hot air, drying, characteristic curve, drying technology.*

Introduction

Raw silk, the natural fibre known as the queen of fibres, is facing the challenge of rapidly emerging artificial and chemical fibres as well as various ones with special functions. However, silk fabrics are still extensively favoured by consumers because of their unique advantages, including elegance and excellent texture. Relevant production equipment, including textile machines (e.g., automatic reeling machines and high-speed looms), adapted to modern science and technology has emerged. The silk industry remains an ancient, traditional and special industry compared with the household appliance and transportation industries [1-4]. At least 2.500 years ago, silk was already used by humans in cold-proof and protective clothing [5, 6]. Until the last century, the textile industry, including the silk industry, played a role in accumulating the original capital [7, 8], laying the foundation for industrialisation, and actively promoting societal development [6-13] during the development of advanced countries. Accordingly there are distinct epochal and regional characteristics in the development process of relevant silk production technologies, including the technology for drying silkworm cocoons – the raw material of silk – which is the focus of this article. For example, in the middle of the 20th century, the former Soviet Union and Japan were experiencing the early stage of rapid economic development, and the development of cocoon-drying (silk) technology almost peaked. A large number of Russian [14-16] and Japanese [17, 18] studies have thoroughly discussed the technologies and theories of cocoon drying. In particular, the basic theories of heat transfer were emphasised in the former Soviet Union [14-16], whereas the research in Japan mainly concerned the effects of cocoon-drying technology on the quality of silkworm cocoons (raw silk), especially the denaturation of sericin [18]. Moreover the world-leading hot air cocoon dryer was developed in Japan [17]. During the 1970s and 1980s, Japan entered an era of rapid economic growth, in which the contribution of the textile (silk) industry to the national economy was reduced. Meanwhile China entered an early stage of rapid economic development, in which the silk industry boomed, and research on cocoon drying technology flourished [19-22]. Both the technology and equipment for cocoon drying were studied comprehensively [23-26]. With the rapid development of China's national economy, the proportion of the traditional textile and silk industry in the national economy is decreasing. Of late, the traditional silk industry has been transferring to the developing countries that have just entered the high-speed development stage, including India [27], Uzbekistan, Brazil, Vietnam, and Mexico [28]. Moreover the continuous growth in the world's population and improvements in living standards require textiles with new functions to meet the changing needs, not just for keeping the human body warm [29]. For example, nanotechnology brings multi-functionality to textiles and provides them with special, sometimes unexpected benefits [30].

As is well known, cocoon fibre is an important material for textile and silk. Today cocoon drying technology has been frequently reported (mostly in non-English papers) in many countries, such as microwave [31], infrared [25, 32], coal-fired flue gas [24], superheated steam [33] and solar drying [34, 35]. In practical production, however, hot air drying, a drying technology with hot air as the drying medium, has been used most extensively. Generalised hot air drying can also include the aforementioned flue gas drying, as well as superheated steam drying [36-38]. These technologies have the advantages of simple equipment maintenance, stable heating temperature, better compliance with the requirements of material drying technology, and high drying capacity. However, a silkworm cocoon comprises both porous fibres (cocoon layer) and an organism (silkworm pupa). The outer cocoon layer has a low moisture content (about 12-15%) [39], whereas the internal pupa inside the cocoon shell has a high moisture content of above 70%, and the vast majority of that moisture must be removed during the drying process. Cocoon drying removes the moisture in the pupa body through the cocoon layer [40] without damaging the fibres in the cocoon layer. Meanwhile if the cocoon is not dried promptly, the cocoon quality can be damaged either by the effect of the steaming-hot phenomenon or by the development of the silkworm into a moth [41]. Therefore the object of cocoon drying is highly specific and its process very difficult and time-sensitive [42, 43]. In fact, many Chinese scientists have carried out a series of studies on cocoon drying, but little information can be obtained from other countries owing to most of the relevant Chinese articles being unpublished by English journals. To share Chinese cocoon drying technology with international counterparts, we describe the characteristic curves of cocoon drying and discuss the relationship of the temperature and humidity of the drying medium (hot air) with the cocoon drying speed using the enthalpy psychrometric chart. Furthermore combined with the characteristics of cocoon drying and its effect on cocoon quality, we review the principles for establishing the hot air temperature and humidity, as well as the specific drying technology in terms of equipment design and technological management of hot air cocoon drying.

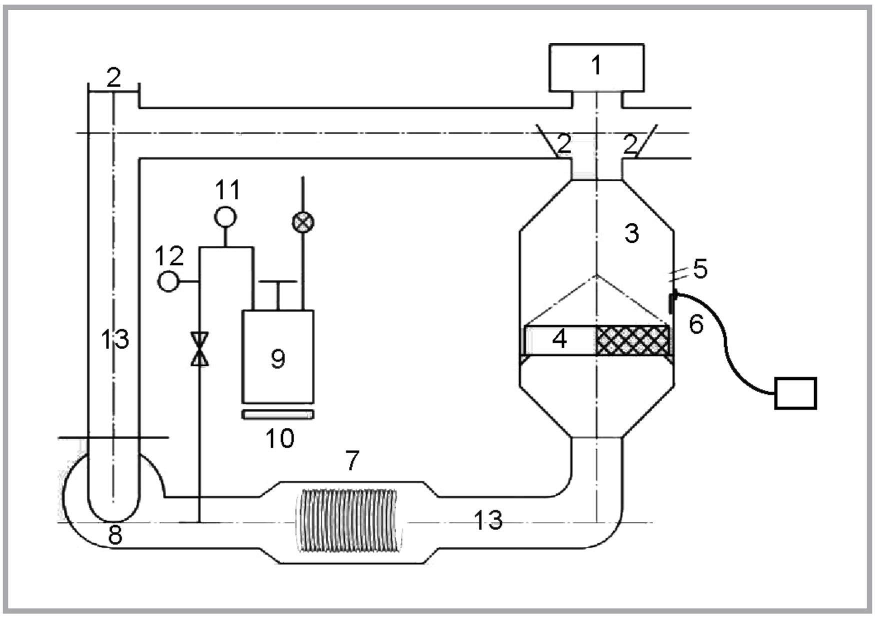

Figure 1. Schematic diagram of the dryer for the experiment: 1) check weigher, 2) air duct baffle, 3) drying room, 4) reticulate basket, 5) observation hole, 6) thermocouple temperature measuring system, 7) electric heater, 8) fan, 9) gas storage bin, 10) heater, 11) steam flow meter, 12) piezometer, 13) air duct.

Characteristic curves of cocoon drying

The three characteristic curves of cocoon drying refer to the drying rate (dried material mass/original material mass) vs. the drying time, the drying speed vs. the drying rate, and temperature susceptibility vs. drying rate curves in the drying process under constant drying conditions, which are referred to as the cocoon drying curve, drying speed curve and temperature susceptibility curve, respectively. These characteristic curves form an important basis for studying the patterns, designing equipment for cocoon drying, and for configuring the technological conditions of cocoon drying. However, cocoon drying involves a preheating process (preheating stage) for killing the pupa. The time consumed by the preheating stage is minor relative to the entire drying process. Nonetheless due to the physiological resistance of live pupae, the time required for pupa killing has a substantial impact on the drying speed. Therefore in addition to the characteristic curves of the entire drying process, we also elaborate on the three characteristic curves of the preheating stage in this section. ***Figure 1*** shows a schematic diagram of the dryer for relevant experiments. For hot air drying, the steam system (9, 10, 11, and 12) was closed.

Characteristic curves of the entire drying process and critical drying rates

Three characteristic curves of cocoon drying are depicted in ***Figure 2***. Under consistent technological conditions, the drying curve is a negative exponential function with base e (***Figure 2.a***) [44]. Historically (including in the professional textbooks of Chinese universities) the entire drying process has been divided into the constant-rate drying stage and

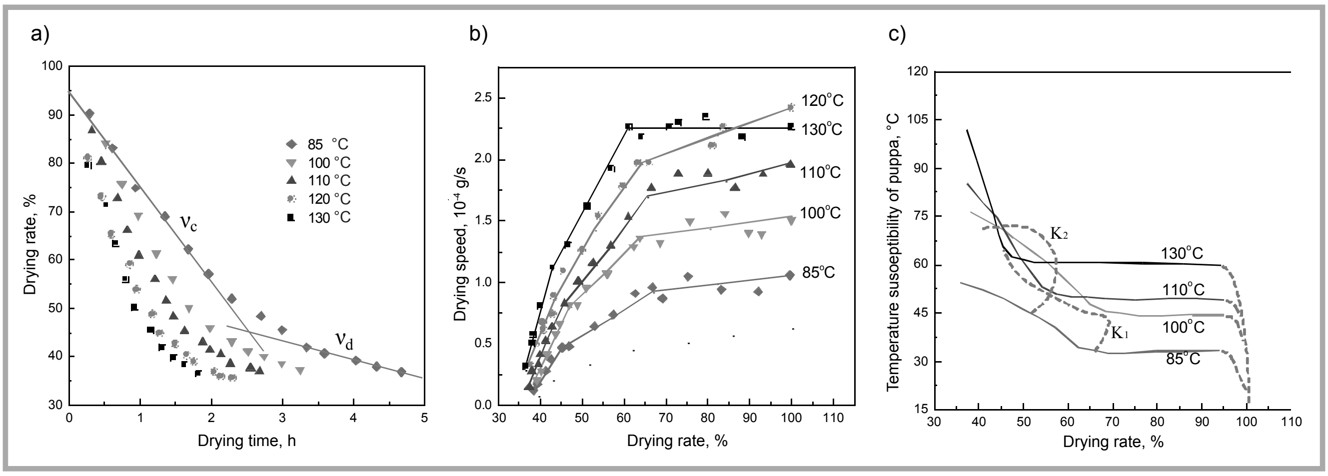

Figure 2. Characteristic curves of cocoon drying at different drying temperatures: a) drying curves, b) drying speed curves and c) temperature susceptibility curves of pupa [44] (redrawn based on original figure data).

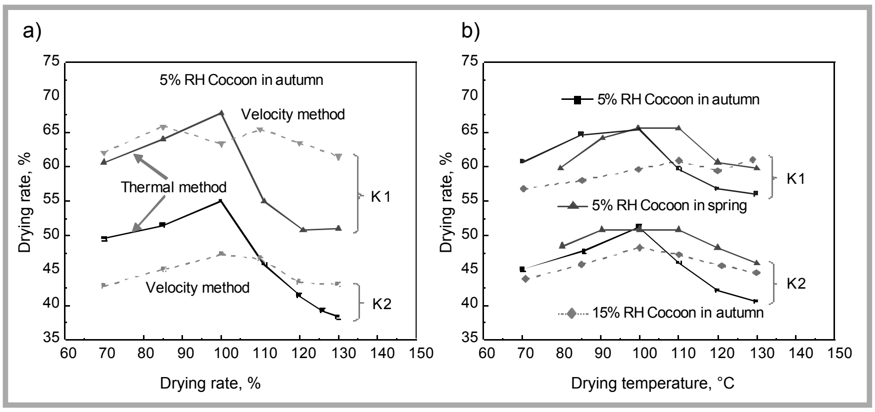

Figure 3. Critical drying rates in cocoon drying: a) Critical drying rates obtained using the velocity method (dashed lines) and thermal method (solid lines) and b) average critical drying rates obtained using the two methods under different technological conditions [44]. RH: Relative Humidity.

falling-rate drying stage in accordance with tangential lines and on the drying curves (***Figure 2.a***). However, the physical correlations between the "constant-rate" and "falling-rate" are unclear in ***Figure 2.a***. With the drying speed curves in ***Figure 2.b***, the drying process is clearly divided into constant-rate, first falling-rate, and second falling-rate stages. The critical drying rates G_{K1} and G_{K2}, corresponding to the critical points K_1 and K_2, respectively, and the fitting result for each curve are also provided in the same figure [44]. Thus cocoon drying involves two falling-rate stages, each of which follows a linear pattern (***Figure 2.b***). The only difference between the two falling-rate stages lies in the higher falling rate during the second falling-rate stage. Moreover ***Figure 2.b*** shows that the higher the drying temperature, the more significant the falling-rate process. The temperature susceptibility curves of the cocoon layer show little change; subtle turning points appear in the deceleration stage only when specific technological conditions are altered. By contrast, the temperature susceptibility curves of the pupa show typical characteristics of wet materials (***Figure 2.c***). The preheating stage (***Figure 2.c***, dotted line on the right) is followed by a prolonged isothermal process; subsequently, there is a rapid heating process that then gradually slows until it nears the temperature susceptibility of the cocoon layer. The purpose of naked pupae drying is to directly observe the time of its death and to compare the drying speed conditions before and afterwards.

Based on the three characteristic curves of cocoon drying, it is clear that the cocoon drying process can be divided into four stages: preheating, constant-rate, first falling-rate, and second falling-rate. The moisture removed in different stages exists in various forms in the body of the pupa. For example, the moisture removed in the first two stages should be mechanically bound water, while that removed in the latter two stages includes mono-layered adsorbed moisture in the cocoon and pupa layers [39]. However, untimely or excessive removal of the mono-layered adsorbed moisture in the cocoon layer during the drying process may lead to excessive moisture loss from the cocoon layer, thereby causing serious denaturation of sericin, which ultimately affects the quality of the cocoons and raw silk. Therefore the technological conditions of cocoon drying must be configured based on the characteristic curves. To this end, it is critical to accurately determine the critical points on the characteristic curves before any silkworm cocoons are dried [44]. However, inconsistencies in the critical drying rates G_{K1} and G_{K2}, which correspond to the critical points K_1 and K_2, respectively, are obtained based on the drying curve and temperature susceptibility curve (***Figure 3.a***). Thus from the perspective of probability, it may be more representative and reliable to average the two factors. Under constant technological conditions, there is a parabolic relationship between the critical drying rate and the temperature. Regarding the relationship with humidity, the higher the humidity, the lower the critical drying rate (***Figure 3.b***).

Characteristic curves of the preheating stage

The task of pupa killing is completed in the preheating stage [40]. A common belief is that "the increase in temperature should not be too fast in the preheating stage" [5]; otherwise, it will cause excessive moisture loss in the cocoon layer and result in denaturation of the sericin, thereby degrading the cocoon quality. Drying speed and temperature susceptibility curves of the preheating stage are elaborated in this section. Because the time required for pupa killing has a great impact on the drying speed, the time required for this is primarily discussed.

Time required for pupa killing and temperature susceptibility of the pupa body

The time required for pupa killing is defined as the time span from the start of drying to the death of the pupa at different drying temperatures. ***Figure 4.a*** shows that 1) whether considering individual naked pupae or all naked pupae or all pupae within the fresh cocoon layer (hereinafter referred to as cocooned pupae), the time required for pupa killing rapidly decreases with the rise of the drying temperature; however, when the drying temperature exceeds 100 °C, the time required for pupa killing becomes relatively stable and decreases slowly; and 2) the time gap between the start of the naked pupa's death and that of all naked pupae markedly decreases at drying temperatures above 100 °C. Therefore the drying temperature should rise to above 100 °C as soon as possible at the preheating stage. This will not only accelerate the drying speed but also reduce the difference in the time required for pupa killing between various cocoons [40], which is critical for reducing the heterogeneity of the degree of drying in both quantitative and qualitative aspects. ***Figure 4.b*** presents the temperature susceptibility (regression) curve of pupae at the time of death. At various drying temperatures between 70 and 130 °C, the temperature susceptibility of pupae ranges between 40 and 50 °C for the deaths of individual naked pupae and between 45 and 65 °C for the deaths of all naked pupae. In most cases, cocooned pupae die when the temperature reaches the range of 50 to 55 °C [40].

Moreover ***Figure 4.b*** shows that in approximately half the range of drying temperatures, the temperature susceptibility of pupae is higher for the deaths of all naked pupae than for those of cocooned pupae. This does not mean that naked pupae are difficult to kill, as difficulty in pupa killing is also related to time. Therefore pupal death can be measured by the

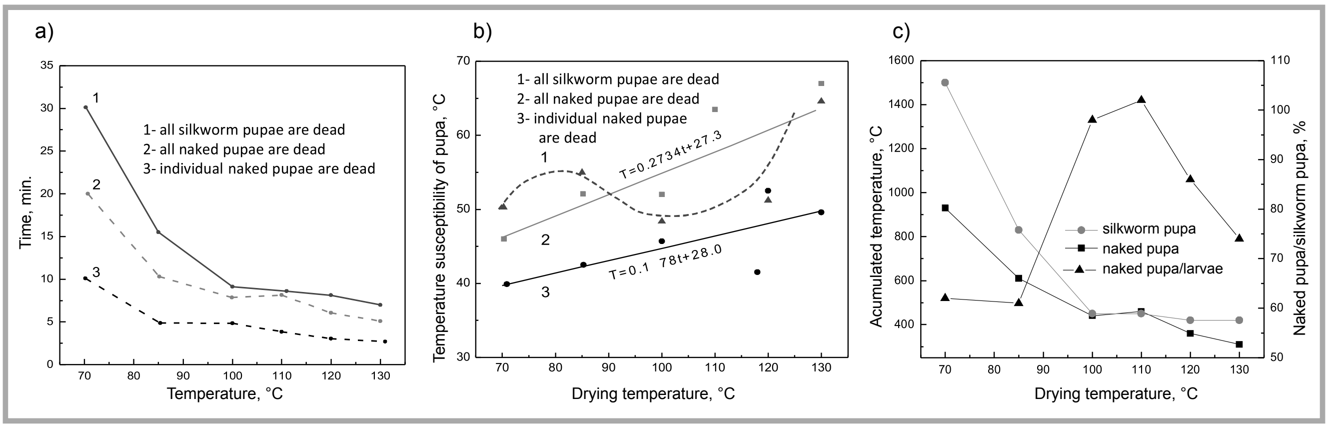

Figure 4. *Time required for pupa killing: a) temperature susceptibility of pupae at death, b) accumulated temperatures and c) the ratio between naked pupae and cocooned pupae [40].*

so-called accumulated temperature-the product of the time required for pupa killing and the temperature susceptibility (fitted value) of the pupa at death (***Figure 4.c***). Moreover it is apparent that, except for one point, the accumulated temperature when all cocooned pupae are dead is higher than that when all naked pupae are dead. On average, the accumulated temperature at the death of all naked pupae is only about 80% of that at the death of all cocooned pupae, indicating that it is relatively easy to kill naked pupae. It is worth mentioning that the accumulated temperature for naked pupae only accounts for about 60% of cocooned pupae at a drying temperature of 85 °C or lower, indicating that the cocoon layer strongly protects the pupa within this temperature range. However, the protective effect is markedly reduced when the drying temperature reaches 100 °C or higher [40]. Furthermore, ***Figure 2*** and the pupal temperature susceptibility curve (data not shown) indicate that at lower drying temperatures, pupa killing lasts almost throughout the entire heating process; however, at higher drying temperatures, pupa killing only accounts for approximately half the heating process, and the time required for heating is relatively short. These findings indicate that higher drying temperatures allow for rapid killing of pupae and reduce variability in the time required for pupa killing.

Drying speed curve of the preheating stage

Figure 5 shows that at different drying temperatures, there is a significant turning point in the drying speed before and after the death of the naked pupa. The rate of change in the drying speed of naked pupa significantly increases after this turning point. Combining ***Figure 4*** with ***Figure 3***, it is found that the turning point in the drying speed of naked pupae coincides with the death of all naked pupae at various drying temperatures [40]. Therefore the emergence of the turning point is due to the death of pupae and the subsequent loss of biological resistance. The significant increase in the drying speed after pupa killing is consistent with previous results commonly obtained using dead and live pupae at the beginning of the experiments.

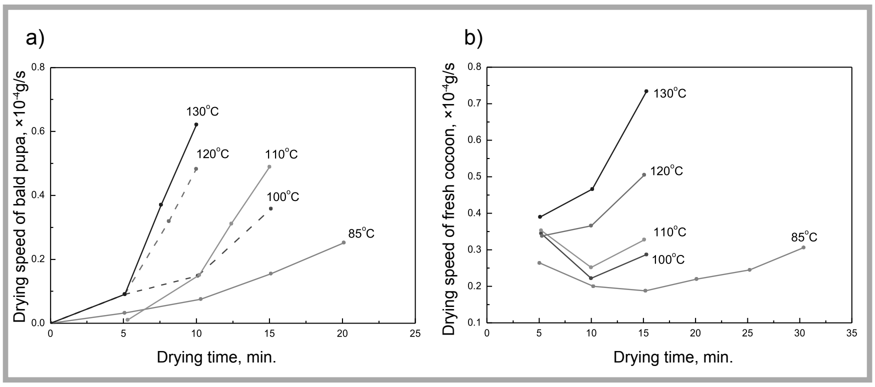

Figure 5. *a) Drying speeds of naked pupae and b) fresh cocoons at different drying temperatures [40].*

As shown in ***Figure 5.a***, the drying speed curves of the fresh cocoon exhibit different variations before and after pupa killing compared with those of the naked pupa. First the trend at drying temperatures of 120 °C or higher is described as follows: the variation in the drying speed of fresh cocoons is somewhat similar to that in the drying speed of naked pupae; however, the increment in the drying speed after the turning point is smaller, and the emergence of the turning point is delayed by several minutes for fresh cocoons compared with naked pupae. This may be because for the former, the initial water evaporation from the cocoon layer results in a certain drying speed; after the turning point, the dead pupa has lower temperature susceptibility and worse dehydration conditions compared with a naked pupa at the same drying temperature (***Figure 4.b***), thus its change is smaller than that of naked pupa. For the latter, a visual explanation can be obtained from ***Figure 2***: the death of cocooned pupae requires more time than that of naked pupae.

Next the situation at a drying temperature of 110 °C or lower is summarised. There is a minimum value in the parabolic relationship between the speed and time of cocoon drying; the lower the drying temperature , the longer the minimum drying time. Although this drying speed curve seems to be unusual, it is not difficult to explain. At the lower drying temperature of 85 °C, the death of cocooned pupae takes 15 min (***Figure 4.a***). Within this time span, the drying speed of the pupa's body is extremely slow, as revealed by the analysis shown in ***Figure 4***. That is, before the death of the pupa, the dry-

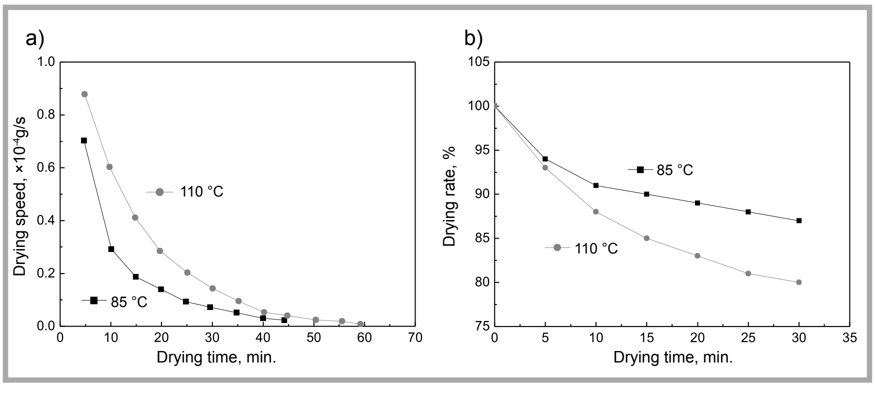

Figure 6. *a) Drying speed and b) drying rate, curves of a fresh cocoon layer at different drying temperatures [40].*

ing speed of the cocoon mainly depends on the drying speed of the cocoon layer. ***Figure 6.a*** depicts the drying speed curve of a fresh cocoon layer. At the drying temperature of 85 °C, the drying process markedly decelerates between 5 and 15 min. In particular, the drying speed decreases faster within the first 5 min of this 10-min time interval, which is consistent with the variation in the drying speed of fresh cocoons in the same time interval at 85 °C in ***Figure 5***. After 15 min, i.e., following pupa killing, the drying speed of the cocoon layer is very slow, while that of the cocoon mainly depends on the pupa drying speed; the drying speed of the cocoon goes faster with constant increases in the drying speed of the pupa.

In short, for a fresh cocoon, a higher drying temperature can kill the pupa rapidly; when the drying speed of the cocoon layer is relatively high, the pupa dies and begins to dry rapidly. Thereforeno deceleration is observed on the drying speed curve during the preheating stage, and there is no way to cause moisture loss from the cocoon layer. By contrast, a lower drying temperature kills the pupa more slowly; the moisture inside the pupa's body cannot evaporate in a timely manner, thus leading to a reduction in the drying speed and a continuous decline in the moisture content of the cocoon layer. ***Figure 6.b*** shows that the drying rates of the fresh cocoon layer are 93% and 90%, corresponding to the turning points of the drying speed of naked pupae in ***Figure 5.a*** at the drying temperatures of 85 °C and 110 °Cand to the drying times of 5 min and 15 min, respectively. In other words, with regard to the absolute value, the cocoon layer loses more moisture at lower temperatures during the process of heating at different drying temperatures. Therefore rapid heating in the preheating stage does not necessarily cause moisture loss from cocoons. With hot air cocoon drying technology, rapid heating under the experimental conditions will not cause excessive moisture loss.

Technological configuration during different stages of cocoon drying

A reasonable drying technology possesses sufficient drying capacity, ensures timely processing of fresh cocoons, and prevents the occurrence of the steaming-hot phenomenon (moisture in the exhalation of live pupae cannot be diffused rapidly, thereby forming a stuffy environment and affecting cocoon quality) and moths hatching (cocoon layer is damaged by moths) in fresh cocoons. In addition, the quality of cocoons must be ensured. Moreover the drying technology should take into account energy conservation, labour savings and cost reduction. As stated above, the subject of cocoon drying is unique, but the drying technology is difficult and time-sensitive. Meanwhile various cocoon drying equipment, reeling (producing raw silk from cocoons) equipment, cocoon varieties, and even climatic conditions will affect the configuration of cocoon drying technology to various degrees. Therefore the drying technology should be configured fully and rationally depending on experimental investigation of the exact circumstances.

However, various stages of cocoon drying show distinct characteristics in terms of drying speed and temperature susceptibility. Therefore the properties of the characteristic curve for cocoon drying form an important basis for configuring cocoon drying technology. For instance, the constant-rate stage is characterised by a high drying speed, a large gap between cocoon the temperature susceptibility and hot air temperature, and by nearly constant values for the drying speed and temperature susceptibility. During this stage, a large amount of (vaporisation) thermal energy is required to maintain the rate of water vaporisation. It has been calculated that more than 60% of the total moisture should be removed during the constant-rate stage [44]; less than 40% of the total moisture is removed in the falling-rate stage, which has lower drying temperatures and higher cocoon temperature susceptibility. From the perspective of protecting cocoon quality, during actual production, the drying temperature of the falling-rate stage should not be very high. Therefore we should focus on increasing the temperature in the constant-rate stage to improve the drying speed. Then we address how the drying capacity and cocoon quality are affected by increasing the drying temperature during the constant speed stage. Below we clarify these two relationships and then review how to configure the technology based on the properties of the characteristic curve for cocoon drying.

Relationship of hot air temperature and humidity with drying capacity

Chen and Zhu (1993) [45] and Chen (1997) [42] assessed the relationship between the hot air temperature and humidity of the drying medium with the cocoon drying speed using the enthalpy psychrometric chart. They described the relationship of temperature and humidity with the drying speed at different hot air temperatures and humidity conditions. As shown in ***Figure 7.a***, when the hot air temperature (t_c) is greater than or equal to 100 °C and the relative humidity (φ) is lower than 10%, the effect of t_c on the drying speed V (speed coefficient, v_t) is much higher than that of the relative humidity φ (v_φ); that is, t_c exerts a significantly greater effect on the drying speed than does the relative humidity φ. When t_c is lower than 100 °C, the increment of V due to changes in φ is similar to that observed at $t_c \geq$ 100 °C, whereas v_t is lower than v_φ (in some cases even approximately half or less than half of v_φ) [42, 45]. However, it should be noted that although the drying capacity increases with an increase in the drying speed, these two parameters are not equal in numerical values. Because the drying time τ is inversely proportional to the drying speed V, the reduction rate of the drying time (η'_τ) resulting from an increase in the

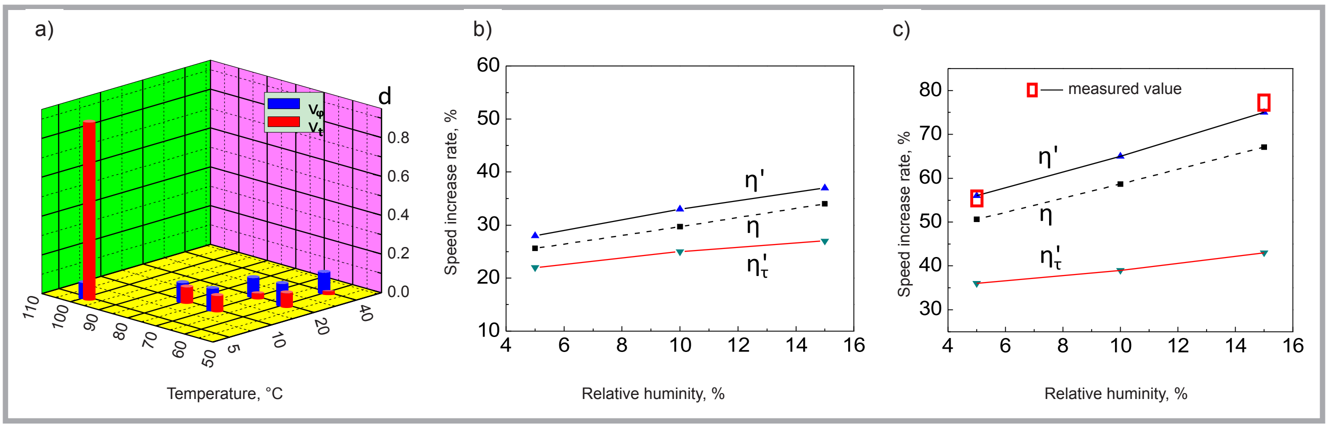

Figure 7. *Relationship of temperature and humidity with the speed and capacity of cocoon drying in different hot air temperature and humidity conditions. a) effects of hot air temperature and humidity on the cocoon drying speed (speed coefficients v_t and v_φ) [42, 45], (b, c) increment of the drying speed and capacity in different temperature and humidity conditions, b) t_c ascending from 105 °C to 120 °C, and c) t_c ascending from 100 °C to 130 °C [45].*

drying speed from V_0 to V_2 can be calculated as follows:

$$\eta'_\tau = \left|\frac{\Delta\tau_{02}}{\tau_0}\right| = \frac{\tau_0-\tau_2}{\tau_0} = 1-\frac{\tau_2}{\tau_0} = 1-\frac{V_0}{V_2} = \frac{1}{1+\eta'}$$

η'_τ can be solved using the above formula and is shown in ***Figures 7.b***, ***7.c***. At φ = 5-10%, increasing t_c from 105 °C to 120 °C can improve the drying capacity by more than 20%, and increasing t_c from 100 °C to 130 °C can improve the drying capacity by more than 35%. The increment of the cocoon drying capacity is far less than that of the drying speed. Meanwhile high-temperature drying is only available for the constant-rate stage, being unsuitable for the falling-rate stage. Therefore the increment of the hot air drying temperature is even smaller for the entire process of cocoon drying. Nonetheless increasing the drying speed of the constant-rate stage is the most effective method at $t_c \geq 100$ °C. For conditions of t_{c0} <100 °C, the relationship between φ and t_c can be predicted qualitatively based on the relationship of v_t and v_φ in ***Figure 7.a***: in the range of t_c = 60-70 °C and φ = 20-40%, the impact of v_φ on the cocoon drying speed is much higher than that of v_t.

Relationship between the hot air temperature during the constant-rate stage and cocoon quality

Many studies have shown that hot air temperatures of > 130 °C during the constant-rate stage reduce cocoon quality [46]. However, hot air temperatures of 115-125 °C during the constant-rate stage will not damage cocoon quality, instead typically resulting in more good than harm [47, 48]; and they are also well adapted to the gradually increasing demands of automatic silk reeling machines for raw cocoons. ***Figure 8*** and ***Figure 9*** present the experimental results of Chen and Zhu (1993) [45] and Chen *et al.* (1992a) [33] regarding the relationship between air temperature and cocoon quality during the constant-rate stage, indicating that it is practical to enhance the drying capability by increasing the air temperature. Spring and autumn cocoons were used in Chen's experiments. Moreover the same batch of cocoons was compared during the drying processes. Meanwhile a maximum hot air temperature of 125 °C was used during the constant-rate stage on the latest drying equipment. This also confirms that it is feasible to use hot air temperatures of up to 125 °C during the constant-rate stage of cocoon drying.

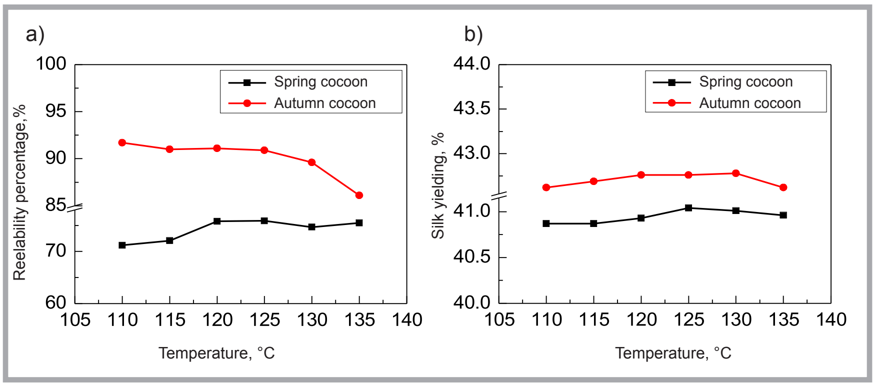

Figure 8. *Relationship between air temperature during the constant speed stage and cocoon quality [45]: a) temperature vs. reelability percentage and b) temperature vs. silk yielding.*

Characteristics of superheated steam drying

So-called superheated steam can be defined as a kind of steam of high temperature that is generated by continually heating dry saturated steam. Superheated steam drying is a new drying technique in which superheated steam directly contacts with materials and heats them [49-51]. It is a heat medium with little pollution, large heat capacity, strong drying capacity and high thermal efficiency. Chen JY and Chen SR (1989) [49] studied the allocation of superheated steam in silkworm cocoon drying.

Furthermore results showed that the drying curve with the medium of superheated steam was similar to that with hot air. Apart from silkworm cocoon drying, superheated steam processed more effective heat exchange than hot air owing to its low molecular weight and strong force of penetration into the cocoon shell. Thus the larger amount of heat release of superheated steam on the surface of the pupa body accelerated the drying. During the constant-rate stage, the temperature susceptibility of the pupa body with 110-135 °C superheated steam drying was 10 °C higher compared to hot air drying. The temperature of the cocoon

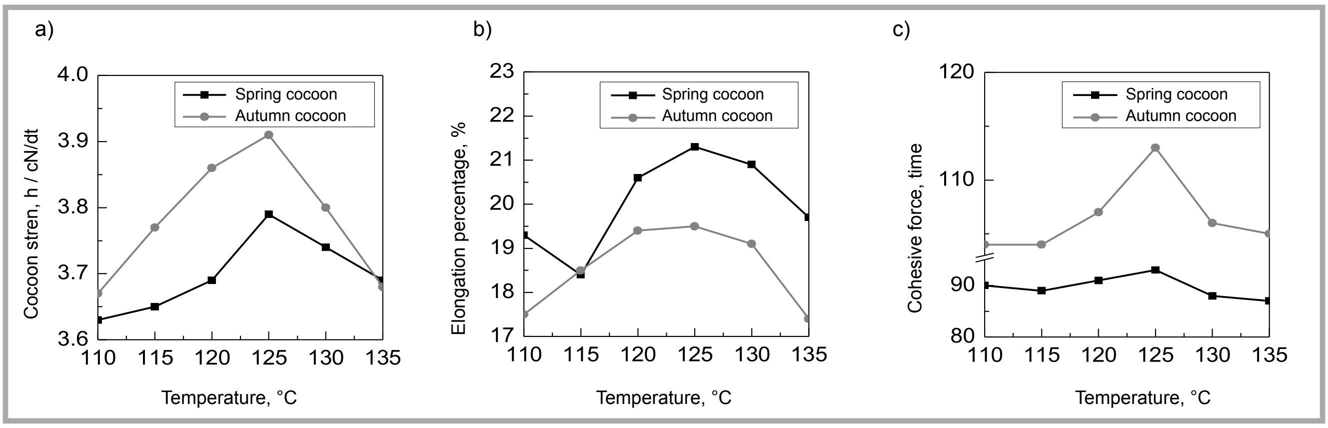

Figure 9. *Relationship between the hot air temperature of the constant speed stage and the mechanical properties of silk [33]: a) temperature vs. strength, b) temperature vs. elongation percentage, and c) temperature vs. cohesive force (redrawn from original figure data).*

shell and cocoon cavity was also raised, but it was still 20-26 °C lower than the ambient steam temperature, and hence the superheated steam could change into wet steam with condensation water while penetrating the cocoon shell, which helped to protect the cocoon shell from losing much moisture. Moreover superheated steam with high permeability is a gaseous water molecule, which can lead to homogeneous denaturation of sericin and improve the solubility property. In terms of appearance, the pupa's body colour with superheated steam drying was brown, while the pupa's body colour with hot air drying was a bit yellow. In addition, the pupa body colour uniformity of superheated steam drying was better than that of hot air drying. However, if superheated steam was still adopted in the falling-rate stage, the drying temperature was usually over 100 °C, which, in turn, led to excessive sericin denaturation and quality reduction of the silkworm cocoon. Thus the optimum was that superheated steam be adopted in the constant-rate stage and hot air in the falling-rate stage. It must be noted that this superheated steam drying technique is not currently promoted in China because the silkworm cocoon drying process is not continuous and season-dependent and needs a steam generator.

Configuration of drying technology

Configuration of drying temperature during the preheating stage

According to the above analysis of "characteristic curves of the preheating stage", this drying stage mainly aims to heat the cocoon and kill the pupa. Rapid heating during the preheating stage is conducive to rapidly killing the pupa and enhancing the drying capacity [52, 53]; it can also reduce the time difference between the deaths of individual pupae, making the time of substantial water evaporation for individual pupae after death more similar across the sample. This is conducive to improving the uniformity of cocoon drying, thus achieving better cocoon quality. As mentioned above, the drying temperature of 120 °C is beneficial for improving the mechanical properties of silk. Therefore during the preheating stage, there is no need to be concerned about moisture loss from the cocoon layer due to rapid heating. Furthermore, it is better to find a way to accelerate the heating (maximum limit of 120 °C or so) and to keep the relative humidity as low as possible [46, 53, 54], for example, 20% or lower.

Configuration of drying temperature during the constant-rate stage

Approximately two-thirds of the moisture content of silkworm cocoons should be removed during the constant-rate stage. Therefore this stage is critical for improving the drying speed and enhancing the drying capacity. Continuously increasing the drying temperature in the constant-rate stage will improve the capacity of cocoon-drying to adapt to the technological developments of modern society. For instance, the development of automatic silk reeling machines requires cocoons with low roughness and low tendency to produce rushing upon cocoons, thereby requiring the use of higher drying temperatures [55]. With respect to the reelability of cocoons (***Figure 7***) and the mechanical properties of raw silk (***Figure 8***), drying temperatures of 120-130 °C are also conducive to improving cocoon quality and facilitating reeling production [33, 45]. Additionally the relative humidity requires adjustment when the drying temperature is increased. An increase in relative humidity from 5% to 15% can prevent excessive moisture loss from the cocoon layer and reduce the rate of dropping end in the inner layer, thereby increasing the reelability percentage of cocoons [56].

Configuration of drying temperature during the falling-rate stage

For the first falling-rate stage, a drying temperature of about 100-110 °C and relative humidity of 10-15% are generally considered to be suitable, while for the second falling-rate stage, although higher temperatures are conducive to enhancing the drying capacity, the cocoons become yellowish and the quality of cocoons is reduced at a drying temperature of 110 °C [57]. According to the investigation, when the drying temperature exceeds 95 °C, mono-layered adsorbed moisture in the cocoon layer will undergo significant disengagement, thereby leading to excessive denaturation of sericin and causing the deterioration of cocoon quality [57]. Therefore in the second falling-rate stage, the drying temperature should be maintained below 95 °C, and the relative humidity maintained between 15% and 30%, to prevent excessive moisture loss from cocoons. In particular, the hot air temperature and relative humidity can be controlled in the ranges of 60-70 °C and 20-40%, respectively, within half an hour before discharging cocoons (final stage of cocoon drying). During this period, the effect of relative humidity on the cocoon drying speed is greater than that of temperature; that is, $v_{\varphi} > v_{t}$ (***Figure 6.a***) [42, 45]. Therefore, we can reduce the relative humidity to improve the drying speed and capacity, while lower air temperatures are used to reduce the heat loss when the cocoon is taken out from the drying machine in order to save energy and allow rapid cooling of cocoons (Because the lower the temperature of the cocoon taken out from the drying machine, the lower the heat loss).

Application of critical points in cocoon drying

Distinguishing of the various stages of cocoon drying is subject to the effects of drying technology conditions. Therefore we can take advantage of the effect of drying technology on the first and second critical points on the drying curve to configure more optimal conditions of cocoon drying technology. For example, we can configure optimised technological conditions (e.g., 120-130 °C hot air) to extend the constant-rate stage, thereby improving work efficiency and saving energy. For the second critical point, we can also apply moisture retention and cooling (≤ 90 °C) to prolong the time of the first falling-rate stage, thereby improving work efficiency and protecting the cocoons. The temperature configuration of silkworm cocoon drying technology (hot air drying and superheated steam drying) is listed in ***Table 1***.

Table 1. *Configuration of silkworm cocoon drying technology [50, 55].*

Drying technology	Preheating stage	Constant-rate stage	First falling-rate stage	Second falling-rate stage
Hot air	Reach the target temperature as soon as possible	110-125 °C	100-110 °C	75-90 °C
Superheated steam	120 °C	130 °C	≤95 °C	

As stated above, the configuration of cocoon-drying technology should take into account the drying capacity, cocoon quality, cocoon variety, and characteristic curves concretely. Furthermore the problems in specific configuration are related less to the drying technology than to the drying equipment [58, 59]. How to design and manufacture drying equipment meeting the aforementioned conditions [53] and to further achieve good management of the drying technology in the process of cocoon drying is the main problem that must currently be resolved [46, 60, 61].

Conslusions

The present study first elaborates on characteristic curves of cocoon drying and then reviews the principles for configuring cocoon-drying technology by taking into account the relationships of the temperature and humidity of hot air with the cocoon drying speed, as well as their effects on cocoon quality. The following conclusions can be drawn based on the results of this research:

1) The characteristics of the cocoon drying curve, drying speed curve, and temperature susceptibility curve of the cocoon layer and pupa body are systematically expounded. Each of the curves can be divided into three stages (preheating, constant-rate and falling-rate). The characteristics of each stage are visually shown on the drying speed curve for cocoons and on the temperature susceptibility curve of pupae: the drying speed curve shows a horizontal stage of constant speed as well as a downward falling-rate stage, and the temperature susceptibility curve of pupae shows a constant temperature and heating process.

2) Changes in the drying speed and temperature susceptibility of a fresh cocoon layer and naked pupa are examined before and after pupa killing in the preheating stage. The temperature susceptibility of cocooned pupae at the time of death generally ranges from 50 to 55 °C. After pupa killing, the drying speed of the dead pupa body increases rapidly, and increasing the temperature for pupa killing cannot only increase the work efficiency but also contribute to the uniformity of cocoon drying. It is recommended that the preheating stage include heating as rapidly as possible, which is conducive to improving the work efficiency and cocoon quality.

3) The effects of the temperature and humidity of hot air on the cocoon drying speed (speed coefficients) are obtained using the enthalpy psychrometric chart. The specific parameter configuration of cocoon drying technology is described in combination with characteristic curves of cocoon drying and the influence of the law of drying technology on cocoon quality: During the preheating stage, the temperature should be increased as quickly as possible, and during the constant-rate stage, the body of the pupa contains a high moisture content; hence, an air temperature of 120-125 °C is recommended; In the deceleration stage, the body of the pupa retains little moisture, and the temperature susceptibility is close to the air temperature, and the drying temperature must usually be maintained below 100 °C. Especially in the hot air temperature ranges of 60-70 °C and relative humidity at 20-40%, changing the humidity results in a greater change in the speed coefficient than changing the temperature; thus, it is feasible to increase the drying speed and, accordingly, improve the drying capacity by reducing the relative humidity.

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