Pei Feng[1,3], Ronggen Zhang[1], Chongchang Yang[1,2*]

Effects on the Stability of the Balloon Shape in the Covered Yarn Process

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[1] **College of Mechanical Engineering, Donghua University,**
Shanghai, 201620, China
* E-mail: ycc@dhu.edu.cn

[2] **Engineering Research Center of Advanced Textile Machinery, Ministry of Education,**
Shanghai, 201620, China

[3] **School of Materials Science and Engineering, Georgia Institute of Technology,**
Atlanta, 30332, USA

Abstract
In the process of producing covered yarn, a single outer wrapping yarn forms a balloon when it rotates at high speed. In this work, we used a mathematical model of a balloon formed by polyamide,which is a common outer wrapping yarn, and verified its feasibility with a group of experimental data. The effects of yarn tension, rotation speed, balloon height and turntable radius on the balloon shape were analysed and the correctness simultaneously demonstrated.

Key words: *balloon shape, covered yarn, numerical simulation, parameters.*

Introduction

A balloon is a common phenomenon in the process of spinning and will affect the performance of yarns hugely. Its shape is influenced by various factors. Lüdick observed and investigated the phenomenon of the balloon in the spinning process in 1881 for the first time [1]. In the 1950s, Mack [2] and DeBarr [3] developed a mathematical model and put forward second-order nonlinear differential equations for the balloon shape and yarn tension. In 1965, Barr and Calting published a treatise based on previous researches, which can be used to analyse the question with no winding tension. In addition, Mack, DeBarr and Calting's [4] researches on the balloon in ring spinning were alomost the most comprehensive in that era.

With the development of computers, it has become easier to solve second-order nonlinear differential equations. Therefore research on balloon equations and the method of solving them has renewed progress. Subhash. K and Batrayan [5-6] came up with balloon equations both ignoring air resistance and established non-dimensional general balloon equations. They firstly gave a numerical solution to quasi-stable state balloon equations in 1989.

Fraser [7-8] regarded a balance equation which described how the yarn crosses the traveller as a boundary condition to solving the balloon equations. The research established the boundary condition of balloon equations. They also studied the effect of the control ring on the stability of the ring-spinning balloon and its stability when the yarn was not uniform [9-12].

In the past 20 years, more works have been done about balloon dynamics, including the balloon's inherent frequency, mode of vibration and the application of a balloon ring. With balloon dynamics, the problems of the resonance and limitation of the balloon can be solved. Besides this, exact solutions to balloon equations ignoring air resistance and approximate solutions considering air resistance [13-19] were reported.

It can be summarised from these literatures that researches of the balloon mostly focus on ring spinning. There have been few reports about the balloon shape in covering technology. In this paper, through numerical simulation and experimental verification, the influence of parameters on the balloon can be obtained. As a result, a group of appropriate parameters can be determined to obtain the largest balloon space. The influence of multivariate effects on the balloon shape can be analysed at higher rotation speed.

Theoretical model

In the covering process, a single outer wrapping yarn is rotated to cover the core yarn, and a balloon is formed when a single outer wrapping is rotated at high speed. The balloon moves the trajectory formed by a yarn around the turntable axis at a considerably high rotation speed. The shape of the balloon is affected by the Coriolis force, air resistance, solidarity, yarn gravity etc, which can be expressed with a balloon curve. According to the research of Subhash K. Batra [6-7] and Zhan Kuihua [14], the factors to be considered are as follows: centripetal acceleration, relative acceleration, Coriolis acceleration, yarn tension, air resistance and gravity.

The space model is shown in ***Figure 1***, $R(r, \theta, z)$ which uses a fixed reference coordinate system. The rotation speed is n, and the origin is set at the covered point.

In practical production, the winding linear velocity of yarn is very small compared to the rotation speed, and air resistance is directly proportional to the square of the velocity. Therefore the air resistance in the direction of the winding linear velocity of yarn can be ignored. Meanwhile the gravity can be ignored due to the light weight of yarn. Therefore the following equations can be established based on Newton's Second Law ***Equation (1)***:

$$m_0 ds(\mathbf{a}_r + \mathbf{a}_\theta + \mathbf{a}_k) = (\mathbf{F}_T + \mathbf{F}_P) ds \qquad (1)$$

Combining equations for acceleration and force, the motion equations of balloon yarn can be obtained in cylindrical coordinates, see ***Equations (2)***, ***(3)***, ***(4)*** and ***(5)***.

Boundary conditions: $r(0) = 0$, $\theta(0) = 0$, $\theta'(0) = 0$, $z(0) = 0$, $T'(0) = 0$, in the place of arm $z = h$, $r = r_a$.

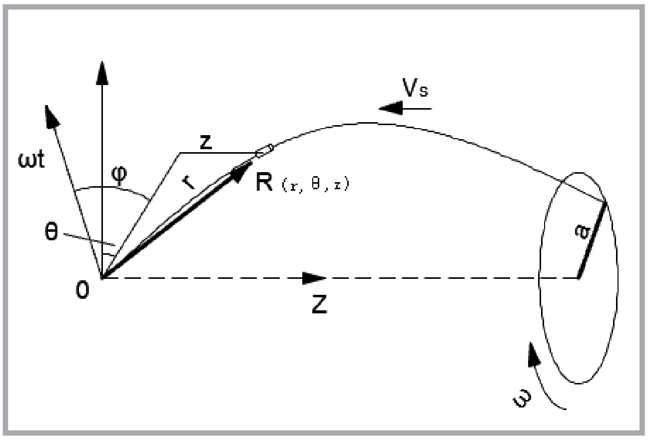

Figure 1. Space model coordinate system.

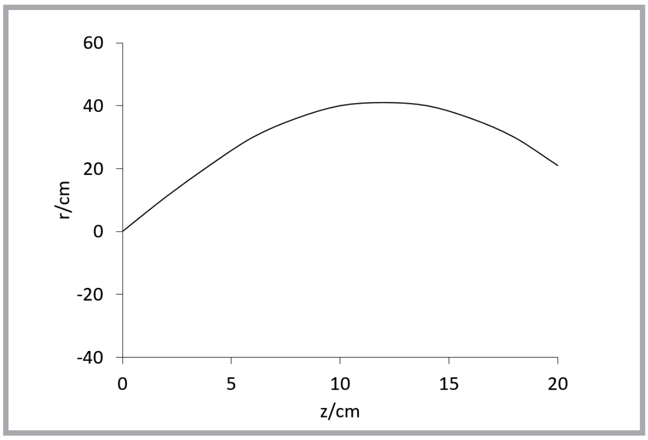

Figure 2. Simulated balloon shape.

The dimensionless parameter w was defined by Fraser [8]. The dimensionless parameters are defined as below:

$$r_w = \frac{r}{r_a},\ \theta_w = \theta,\ z_w = \frac{z}{r_a},\ T_w = \frac{T - m_0 v^2}{m_0 \omega^2 r_a^2},$$

$$P_{nw} = \frac{16 r_a P_n}{m_0},\ s_w = \frac{s}{r_a},\ k = \frac{v}{r_a \omega},\ h_w = \frac{h}{r_a}$$

The dimensionless equations of motion for yarns are given as ***Equations (6)***, ***(7)***, ***(8)*** and ***(9)***.

Boundary conditions: $r_w(0) = 0$, $\theta_w(0) = 0$, $\theta_w'(0) = 0$, $z_w(0) = 0$, $T_w'(0) = 0$, in the place of arm $z_w = h_w$, $r_w = 1$.

According to ***Equations (6)***, ***(7)***, ***(8)*** and ***(9)***, the parameters of the balloon shape can be calculated by a computer.

The linear density of polyamide is 70 dtex, the yarn tension 55 cN, the rotation speed of the arm 3140 rad/s, the winding speed 0.625 m/s, the height of the balloon 200 mm, and the coefficient of air resistance is 1.2. The balloon shape can be calculated via numerical simulation. The result is presented in ***Figure 2***. The largest radius of the biggest balloon is 41.5 mm according to the calculation.

From the results, the balloon shape can be predicted through numerical simulation.

Experimental details

In order to obtain the effect of the balloon shape, a new experimental device with higher rotation speed of covering was set up. The device's rotation speed can reach 30000 r/min because the load is the outer wrapping yarn. A schematic of the high speed covering device is shown in ***Figure 3***.

The single outer wrapping yarn rotates around the core yarn, which is driven by the turntable. The outer wrapping yarn forms a balloon and the core yarn is placed inside the balloon. In the experiments, a Phantom Vision v12.1 high speed camera was used to obtain desired images, which included top, angle, side, and tip close-up. Different values of the rotation speed, turntable radius, linear density and tension were set and are shown in ***Table 1***.

Results and discussion

Effect of Tension

Under the condition that the tension is given, the balloon shape can be obtained by using equations fo the balloon. In order to check the impact of tension, we chose 3 sets of parameters, shown in ***Table 1***.

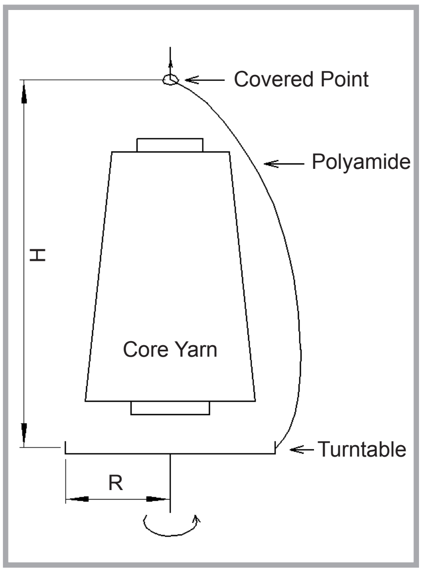

Figure 3. *Schematic of the high speed covering device.*

$$\begin{cases} r'' = \left[T' r' + \left(mv^2 - T\right) r\theta'^2 + mr\omega^2 - 2m\omega v r\theta' + P_n r^3 r' \theta' \omega^2 \sqrt{r'^2 + z'^2}\right] / \left(mv^2 - T\right) & (2) \\ \theta'' = \left[r\theta' T' + 2\left(T - mv^2\right) r' \theta' + 2m\omega v r\theta' - P_n r^3 r' \theta' \omega^2 \sqrt{r'^2 + z'^2}\right] / r\left(mv^2 - T\right) & (3) \\ z' = \sqrt{1 - r'^2 - \left(r\theta'\right)^2} & (4) \\ T' = -m\omega'^2 rr' & (5) \end{cases}$$

$$\begin{cases} r_w'' = \dfrac{-T_w' r_w' + r_w \theta_w'^2 T_w + 2 r_w \theta_w' k - P_{nw} r_w^3 r_w' \theta_w' \sqrt{r_w'^2 + z_w'^2} / 16}{T_w} & (6) \\ \theta_w'' = \dfrac{-r_w' \theta_w' T_w' + 2 r_w' \theta_w' T_w + P_{nw} r_w'^2 \left(r_w'^2 + z_w'^2\right) \sqrt{r_w'^2 + z_w'^2} / 16}{r_w T_w} & (7) \\ z_w' = \sqrt{1 - r_w'^2 - \left(r_w \theta_w'\right)^2} & (8) \\ T_w' = -r_w r_w' & (9) \end{cases}$$

Equations (2), (3), (4), (5), (6), (7), (8) *and* ***(9)***.

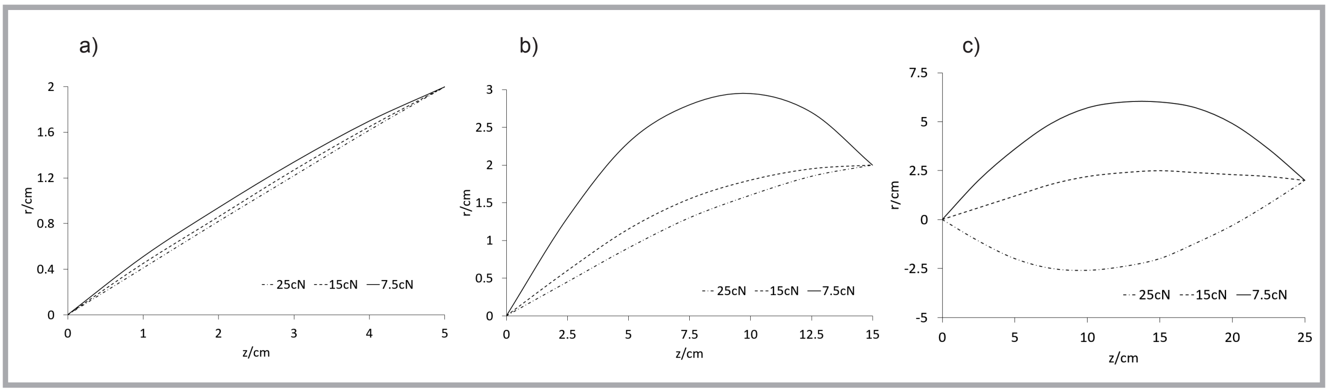

Figure 4. *Plane balloon shape with different tensions: a) balloon height: 5 cm, b) balloon height: 15 cm, c) balloon height: 25 cm.*

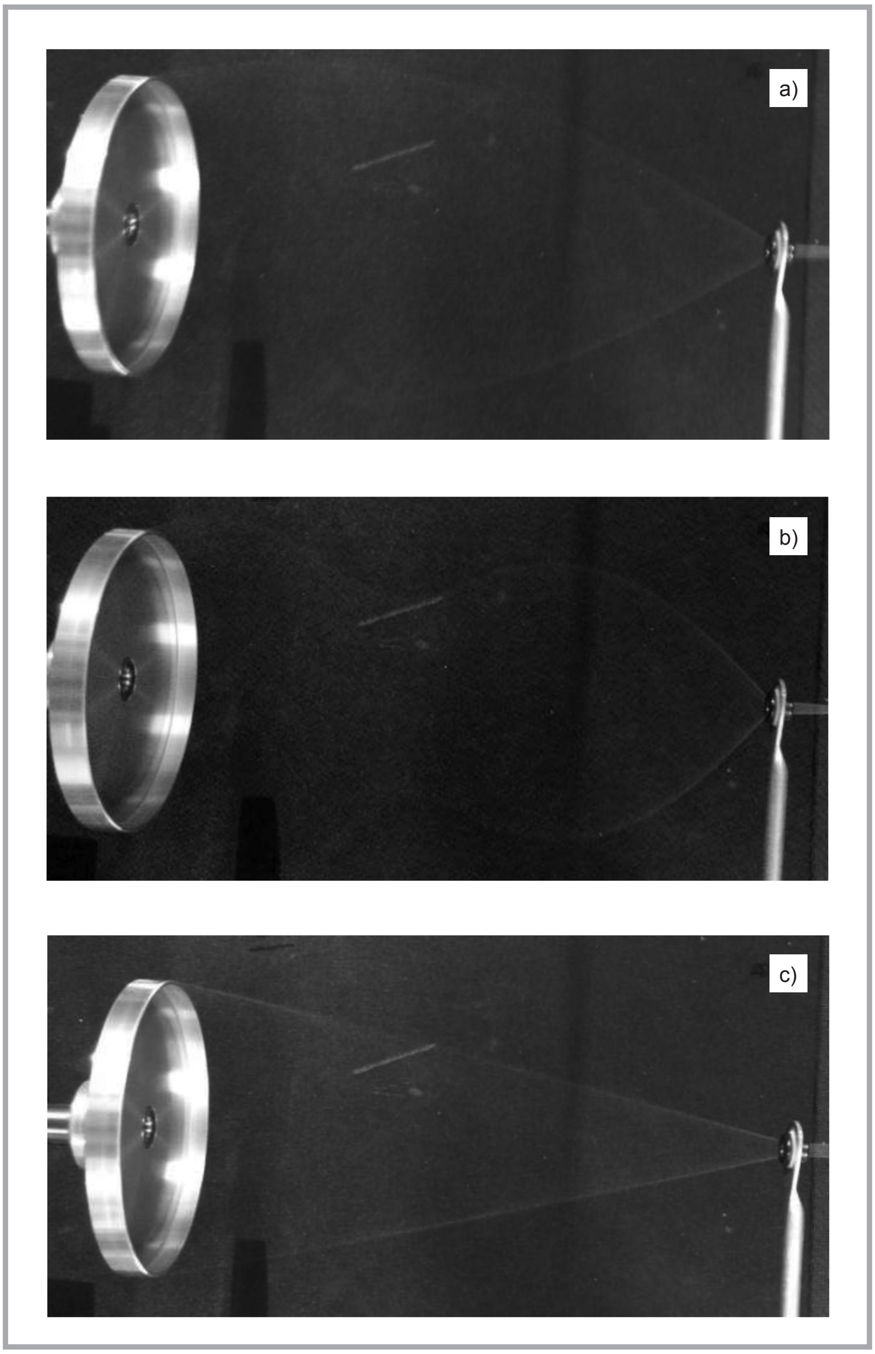

Figure 5. *Balloon shape at different tensions: a) balloon shape with appropriate tensio, b) balloon shape with too large tension, c) balloon shape with too small tension.*

The value of the yarn's linear density is 70 dtex, and the balloon height was set as 5 cm, 15 cm and 25 cm, respectively. In each set, the value of yarn tension in the guide wires was set at 7.5 cN, 15 cN and 25 cN, respectively.

According to the mathematical model, the balloon shapes can be obtained as shown in ***Figure 4***.

According to ***Figure 6***, it can be obtained that:

- Keeping other parameters constant, the smaller the tension is in the guide wire, the larger the balloon radius will be, and vice versa;
- With the same balloon height, linear density of yarn and rotation speed, the number of balloons will change with tension variation. Thus the tension in the guide wire should be controlled as it greatly affects the yarn shape.

Tension is required to reach equilibrium between the outer wrapping fiber and core yarn during the process of covering. The shapes of covered yarn vary with different tensions. From the theoretical analysis, we can see that the initial value of tension was constant when other conditions were settled.

It was verified with experiments that the balloon shape changes significantly when the tension is varied, as shown in

Table 1. *Grouping of experiments.*

Parameter \ Number	1	2	3
Linear density of yarn, dtex	70	70	70
Tension of initial point, cN	7.5 15 25	7.5 15 25	7.5 15 25
Balloon height, cm	5	15	25

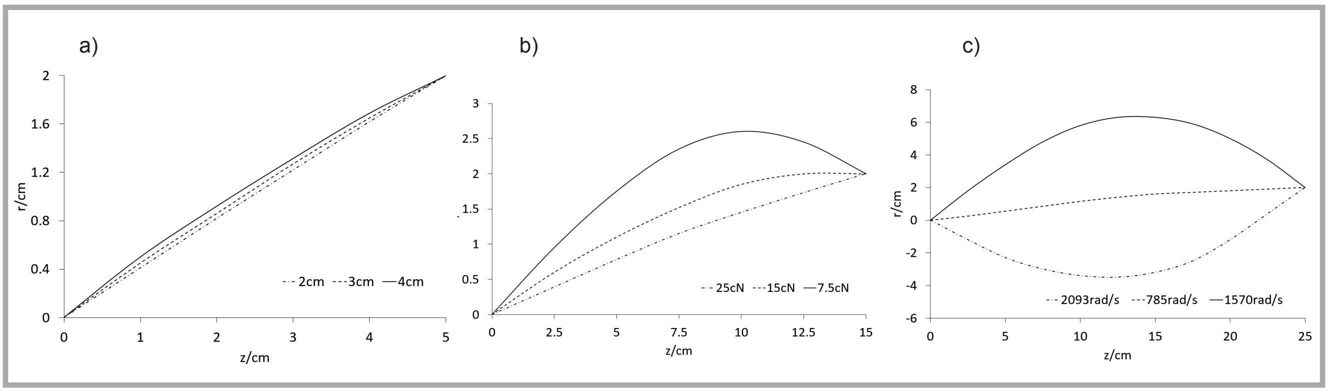

Figure 6. Balloon shape at different rotational speeds: a) Balloon height is 5 cm, b) Balloon height 15 cm, c) Balloon height 25 cm.

Figure 5, and when the tension was in a certain range, the balloon shape was stable and the profile of the balloon's radius was parabolic. The balloon shape became unstable when tension was too large or too small, see ***Figure 5.b*** and ***Figure 5.c***, which is consistent with the theoretical analysis.

Effect of rotational speed

According to ***Figure 6***, it can be obtained that:

- The higher the rotational speed is, the slacker the yarn is, and the bigger the radius of the balloon will be as a result.
- The expansion of the balloon shows certain regularity along with the change of rotational speed. The balloon shapes have different sensitivity to variation in the rotational speed in dependence on the height of the balloon. The greater the balloon height, the more sensitive the change of balloon shape will be to rotational speed changes.
- The balloon has a different number of sections when the rotational speed is different. Therefore the rotational speed and balloon height can be used as two factors which affect the number of balloon sections. This change is abrupt rather than gradual.

The parameters of the experiment were set as below: The yarn density is 70 dtex, the turntable radius 22 mm, the balloon height 200 mm, and the coiling speed is 24 m/min. A tension meter was placed between the turntable and package of outer wrapping yarn. Balloons of stable parabola state were obtained by adjusting the rotational speed and tension. The influence of the rotational speed on the balloon shape and yarn tension was tested, the result of which is shown in ***Table 2***.

The result in ***Figure 7*** shows that the maximum radius of the balloon increased with an increase the rotation speed when the rotation speed was less than 18000 r/min. However, it did not increase when the rotation speed exceeded 18000 r/min.

Effect of turntable radius

According to ***Figure 8*** (se page 72), the following conclusions can be obtained:

- When the balloon height is less than 5 cm, the shape of yarn will be a straight line.
- The change of balloon shape and yarn tension increase with an increase in the turnplate's radius.

In order to verify the impact of the turnt table's radius, experiments were conducted with the following conditions:

Table 2. *Maximum radius of balloon with different rotation speeds.*

Speed, r/min	Maximum balloon radius, mm
12000	34.36
15000	36.75
18000	40.56
21000	40.56
24000	40.56
27000	41.04
30000	41.1

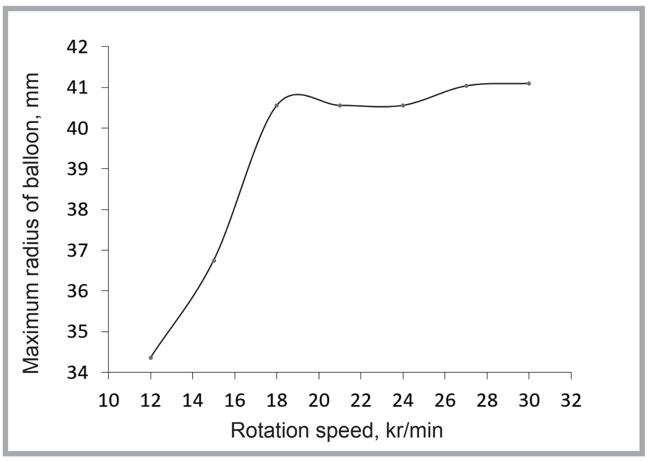

Figure 7. Relationship between rotation speed and balloon shape.

Table 3. *Relation between the balloon height, balloon shape, and tension.*

Radius, mm	Rotational speed, r/min	Tension, cN	Maximum balloon radius, mm
22	15000	6.1	36.75
	18000	8.3	40.56
	21000	13.7	40.56
	24000	19.6	40.56
	27000	27.1	41.04
	30000	36	41.1
40	15000	7.2	49.34
	18000	11.5	50.21
	21000	19.3	51.11
	24000	24	51.21
	27000	32.7	52.53
	30000	42.9	53.15

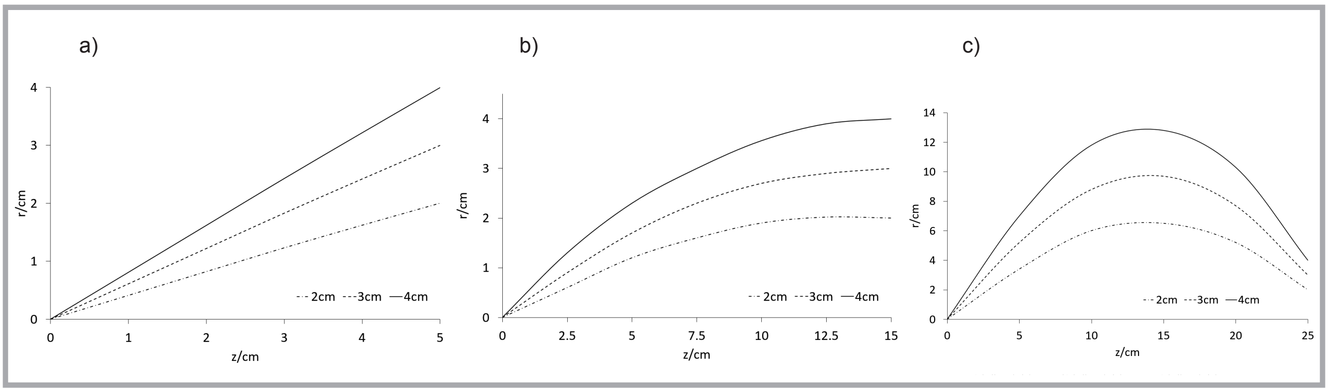

Figure 8. *Balloon shape with different radiuses of the turnplate: a) balloon height: 5 cm, b) balloon height, 15 cm, c) balloon height: 25 cm.*

linear density of yarn 70 dtex, balloon height 200 cm, and twist 500.

As shown in ***Table 3***, the yarn tension and maximum radius of the balloon increase with an increase in the turntable's radius.

Conclusions

A new process and corresponding equipment of covered yarn have been introduced. For the structure of the new covering yarn machine, a mathematical model was developed for the outer wrapping yarn's balloon shape. We set a reasonable boundary condition and got a theoretical curve of the outer wrapping yarn. After that, we conducted an experiment with the same boundary conditions and got an actual curve. A comparison between the two curves verified the feasibility of the mathematical model.

The article expounds the relationship between the different parameters, the balloon shape, and the tension of the outer wrapping yarn at the same balloon height through analysing the mathematical model of the outer wrapping yarn's balloon shape. The current study showed that on the one hand, as the speed of the spindle increases, the radius of the arm grows, the linear density of the outer wrapping fiber increases, the balloon shape dilates, and the tension increases, but on the other hand, as the balloon height increases, the balloon shape dilates, but the tension decreases. This result provides a theoretic foundation for the control of the balloon shape and tension in the process of ultra-high speed manufacturing of covered yarn.

We obtained the influence of various parameters on the balloon shape by theoretical analysis and experiments. The maximum radius of the balloon increases with an increase in the turntable's rotation speed, the turntable's radius and linear density of the outer wrapping yarn as well as with a decrease in yarn tension. However, the maximum radius of the balloon decreases. This result can guide us in choosing the appropriate parameters and obtaining the optimal balloon shape.

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