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Preparation and Characterisation of High Count Yak Wool Yarns Spun by Complete Compacting Spinning and Fabrics Knitted from them

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Abstract
The attentions of the textile industry has been attracted by yak wool due to its excellent properties, environmental friendly characteristics and inexpensive prices. However, the processing of yak wool is difficult due to the larger fiber dispersion and stiffness, especially spun pure and high count yak wool yarn. Therefore, in this paper, a kind of roller-type compact spinning - complete compacting spinning (CCS) was applied to spun pure high count yak wool yarns, in which a special hollow roller made of stainless steel with a strip groove structure on its surface was employed. Based on the mechanism of CCS, the processing parameters for two kinds of yak wool yarns - 20.83 tex and 16.67 tex were set. Then the qualities of the yarns prepared were tested and compared with yak wool yarns spun by common ring spinning. Finally corresponding knitted fabrics were further produced and tested for wearability.

Key words: *yak wool, pure high count yarns, complete compacting spinning (CCS), yarn quality, knitted wearability.*

Introduction

The yak is one of the world's softest and most valuable animals. The Qinghai Tibet Plateau, surrounded by the Himalaya Range, Kunlun Mountains, Qilian Mountains and Altun Mountains [1], gives an average output of 4000 tons each year [2] and comprises 85% of the world's total production [3], making itself the biggest producing area of yak wool in the world. The rest of yak wools are mainly produced in Mongolia, Russia and Central Asia [4]. The hair colour of yaks is strongly influenced by the local climate and can be divided into the coloured and colorless types [5], in which black yak wool makes up 80% of the total survey, followed by blurred black and brown [6]. The environment without pollution makes yak wool more pure and of a natural style. Products made of yak wool meet the environmental and health requirements of modern people, turning yak wool into a top grade textile resource.

Cashmere, with an average diameter of 11 - 19 um and fibre length of 21 - 40 mm [7, 8], has been widely applied in textiles as a high value material due to its outstanding characteristics [9, 10]. Techniques to produce cashmere have been fully developed. It was shown that cashmere fibres with an average diameter between 17 - 21 um were suitable for weaving. When the diameter fell into a narrower range between 17.51 to 18.5 μm, it was applicable to knitting. If the overall length is no more than 34 - 36 mm, the fibres can be used for worsted spinning [11]. But a supplement to cashmere is requisite for China, where overgrazing due to the glut of production is turning grassland into desert. Using wool from China's plentiful yak population can ease overgrazing. Yak wool possesses a similar morphology to cashmere, with an average diameter less than 20 μm and A fibre length of 25 - 35 mm [12]. Furthermore its price is only 1/3 of cashmere's, leading to greater profit margins.

However, at present, conventional yak wool yarns can only be used for low end products since the fibre can only be utilised for spun low count yarn, which generally does not exceed 20.83 tex (48 Nm). This is because on one hand yak wool fibres are relatively thin and delicate, and hence it extremely easy to cause damage to them and/or shorten their length during current carding. As a result, the increased floating fibres are difficult to control during conventional spinning, leading to the occurrence of yarn defects, such as neps. But on the other hand, the stiffness of yak wool makes the fibres fluffy and less cohesive.

Therefore, in this paper, a kind of roller-type spinning CCS [13] was employed for spun high count yak wool yarns, in which

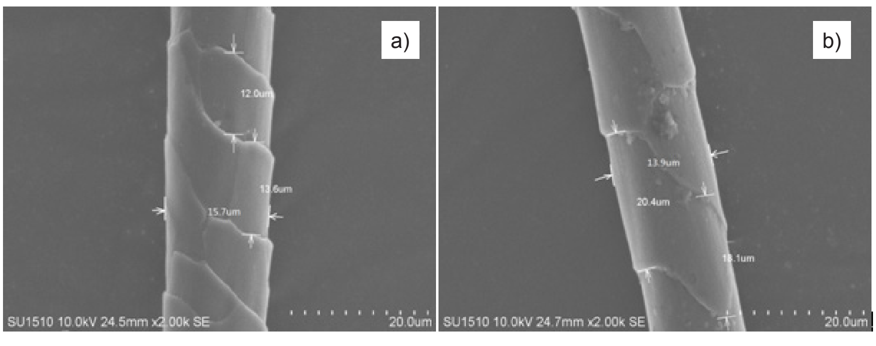

***Figure 1.** SEM images of yak wool fibre (a) and cashmere fibre (b).*

a kind of hollow roller made of stainless steel with a strip groove structure on its surface was employed. The processing parameters for two kinds of yak wool yarns - 20.83 tex (48 Nm) and 16.67 tex (60 Nm) were set, and the qualities of the spun yarns were tested and compared with the yak wool yarns spun by common ring spinning. Finally corresponding knitted fabrics were further produced and tested for wearability.

Fibre properties

In this section, the fibre morphology was analysed by SEM and the length uniformity tested based on 1000 samples.

Fibre morphology

The surface structure of yak wool used in this study was compared with commercial Inner Mongolian cashmere by SEM, shown in ***Figure 1.a*** and ***1.b***. From the figures, it is seen that both of the two animal fibres obtain rich scale structures and similar morphology. The diameter of the yak wool fibre was 15.7 μm larger than that of cashmere at 13.9 μm. Meanwhile the scales on yak wool had larger distribution density and a more close arrangement than cashmere, which could help to explain why the crimp rate and friction of yak wool were larger than that of cashmere, implying better fibre cohesion during spinning. The strength of yak wool was also larger than that of cashmere, indicating more rigid fabric hand.

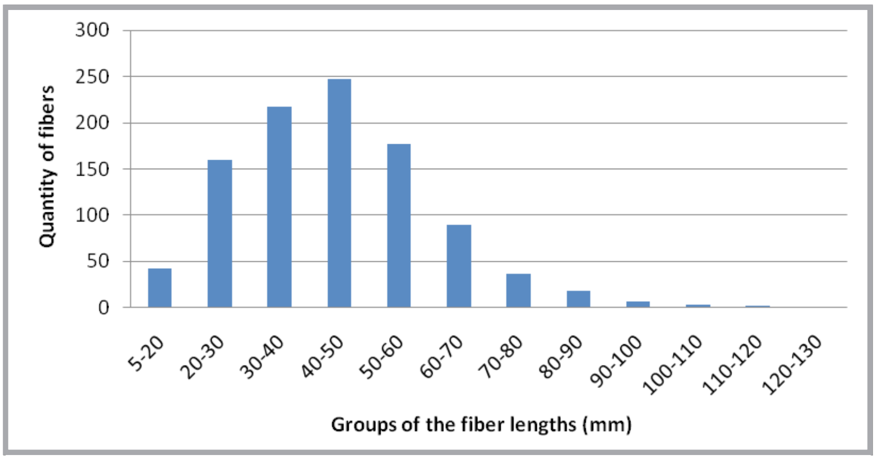

Figure 2. *Distribution of the length of yak wool fibres.*

Length uniformity

Good fibre uniformity was favourable to obtain yarns of high quality [15]. Therefore the fibre lengths of yak wool treated by unique carding processes were divided into 12 groups and the corresponding quantity of fibres in each group was counted, shown in ***Figure 2***. From the figure, it is easy to see that over 80% of the total yak wool fibres were distributed in the range of 20 - 60 mm, in which yak wool fibres with a length range from 40 - 50 mm comprise 24.7%, while fibres with a length less than 20 mm make up only 4.2%.

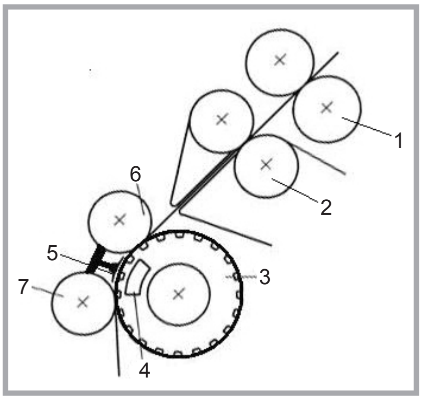

Figure 3. *Complete compacting spinning system (CCS) [13]; 1. Back roller. 2. Middle roller. 3. Hollow front roller. 4. Air suction unit. 5. Airflow guide device. 6. Front top-roller. 7. Output top-roller.*

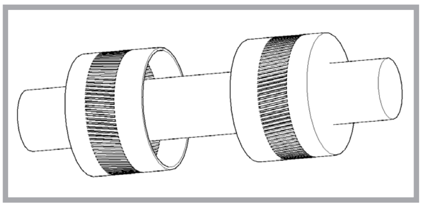

Figure 4. *Hollow front roller [13].*

Yarn spinning

The yak wool rovings produced through unique carding processes were used as raw materials, with a dry weight of 800 tex. Then 20.83 tex and 16.67 tex pure yak wool yarns were spun on common DTM129 ring spinning and DTM129 ring spinning frames equipped with a CCS system. respectively.

Introduction to the CCS

CCS is a kind of roller-type compact spinning, the structure of which is shown in ***Figure 3***, where a stainless steel hollow roller of 56HRC hardness and diameter of 50 mm was equipped [13]. It was quite different from the traditional front roller, with narrow strip grooves engraved on its surface, as shown in ***Figure 4***. In addition, an air suction unit with double slots was equipped in the hollow roller, as shown in ***Figure 5***. As a consequence, airflow with negative pressure could be imposed on the fibre strands to form a compacting area through the slots as well as the strip grooves on the hollow roller during spinning. The bottom of the strip grooves were quadrilateral or trapezoid shaped for better connection between the inner cavity of the hollow roller and the double slotted suction unit. A proper width of the slots on the suction unit was important for the stability and efficiency of the strand bundle, because a narrower width could increase the negative pressure and airflow velocity imposed on the fibre strands. Furthermore a lower distance between the two V-shaped slots on the suction unit was also beneficial for yarn compactness, which can help to improve the yarn evenness and end breakage rate. Meanwhile in order to further improve the compacting effect, an airflow guide device was installed above the hollow roller, and between the front and output top-roller, shown in Part 5 in ***Figure 3***, with its detailed structure given in ***Figure 6***. In the middle of the device, an ellipse-shaped air inlet channel was used to suck the air flow into the compacting area. Double trumpet shaped channels were placed on the left and right sides of the middle air inlet

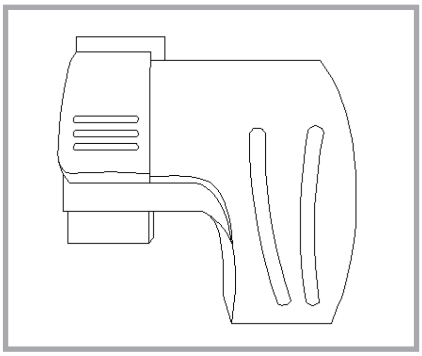

Figure 5. *Air suction units with double slots [13].*

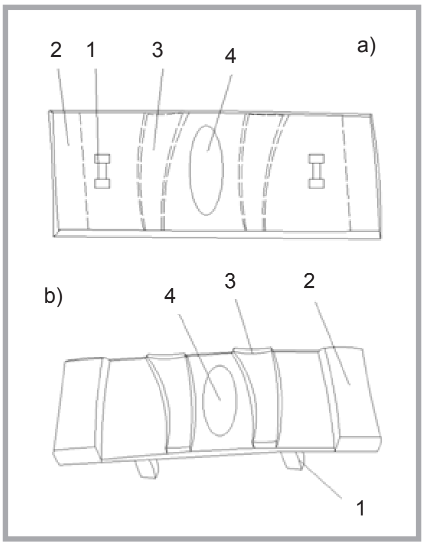

Figure 6. Airflow guide device [13]; a) front structure scheme, b) back structure scheme: 1. Upper part connecting the roller bracket. 2. Bottom supporting part above the hollow roller. 3. Double trumpet shaped channels. 4. Ellipse shaped air inlet channel.

channel, offering mechanical compacting forces to the yarns along the direction of roller rotation. The whole structure of the CCS can increase the compacting length to 30 mm and theoretically decrease the non-controlled area to 0 mm, leading to a real sense of complete compacting [13].

Yarn spinning and evaluation

Based on the similar fibre lengths between yak wool and cotton, a DTM129 ring spinning frame equipped with a CCS system was employed to produce pure high count yak wool single yarns, in which two yak wool rovings were fed to the back roller, i.e. pure high count yak wool single yarns were produced using the compact siro-spinning method. Detailed processing parameters for yak wool yarns of 20.83 tex and 16.67 tex are presented in ***Table 1***. Meanwhile, for comparative analysis, yarns were also spun on a common DTM129 ring spinning frame using siro-spinning technology. In addition, heat setting and folding were applied to the spun yak wool yarns to prepare two folded yarns of 20.83×2 tex and 16.67×2 tex.

Then the qualities of both single and two folded yak wool yarns including yarn tensile properties, evenness and hairiness were tested. The testing methods were as follows. According to the GB/T3916-1997 standard, tensile properties of the yarns were tested by electronic yarn strength testers YG020 and YG068C at a speed of 500 mm/min, respectively. The evenness of yak wool yarns was tested by an Uster Tester 5 for a test time of 0.5 min. The testing speeds for the single and two folded yarns were 400mm/min and 100 mm/min, respectively. Based on the GB/T 2543.2-2001 standard, twists were examined by a Yarn Twist Tester Y331A. According to test standard FZ/T01086-2000, hairiness Testers YG172A and YG173 at a speed of 30 m/min were employed to test the hairiness of the single and two folded yarns, respectively.

The fracture of the yarns was a process where the fibres broke up and/or slipped away from each other [17]. Tensile properties of yak wool single and two folded yarns are shown in ***Table 2***, where it is seen that the breaking force did not show much change between the 20.83tex and 16.67 tex yak wool yarns, which was possibly because of the higher twists employed to produce the 16.67 tex yak wool yarns. However, the breaking force and tenacity of yak wool yarns spun by the CCS were over 12% higher than those of the yak wool yarns spun by common ring spinning. Therefore using the CCS was beneficial to the tensile properties of yak wool yarns. Meanwhile the tensile strength and tenacity of the folded yak wool yarns were much higher than those of the single yarns, which was mainly attributed to the folding treatment , increasing fibre contacts on the surface layer of a single yarn [18] and further leading to higher cohesion among the strands correspondingly. Test results for the spun yarn twist are given in ***Table 2***, which shows that the twists of the two folded yarns decreased when compared with corresponding single yarns, because S twists, instead of the Z twists for single yarns, were adopted to process the folded yarns. The opposite way of twisting made the fibre orientation parallel to the strands, as a result of which the folded yarns used for knitting obtained a soft touch, glossy appearance, as well as more stable twists and structure. Meanwhile the twists of single yarns spun by CCS are similar to those produced by ring spinning.

The coefficient of variation (CV) and the number of thin and thick places are important values to evaluate the evenness of yarns. The test results are given in ***Table 3***, showing that the evenness of the yarns spun by the CCS was improved greatly for both kinds of yarns. Meanwhile the thin and thick places of yak wool yarns were also decreased greatly by using the CCS for both kinds of yarns, because the compacting process improved fibre orientation, leading to better yarn evenness. Furthermore when compared with single yarns, the CV, thin and thick places of the two folded yarns were all improved greatly because the folding process improved their uniformity .

The test results for spun yarn hairiness are shown in ***Table 4***. Yarn hairiness was mainly affected by both spinning and twisting. According to ***Table 4***, by using the CCS, long harmful hairiness (≥ 3 mm) could be greatly reduced. Meanwhile the number of short beneficial hairiness (1 and 2 mm) in the yarns spun by the CCS was close to that of yarns spun by common ring spinning. That is, by using the CCS, long harmful hairiness could be greatly reduced while preserving short beneficial hairiness. Furthermore all hairiness was reduced in the two folded yarns because the folding process improved the uniformity of the yarns.

Table 1. *Processing parameters for 20.83 tex and 16.67 tex yak wool single yarns.*

Processing parameters	Linear density of yarns	
	20.83 tex	16.67 tex
Model of spinning frame	DTM129	
Roller diameter, mm	27×27×50	
Roller distance, mm	29×11	
Ring model	PG1	
Ring diameter, mm	42	
Traveler type	$U1UU_{DR}6/0$	$U1UU_{DR}9/0$
Spindle speeds, s.p.m	9000	8000
Convention moisture regain	15%	15%
Dry weight of spun yarns, g/100 m	1.81	1.45
Physical draft multiple (E_p)	44.21	55.22
Total draft multiple (E_t)	43.74	54.99
Back zone draft multiple (E_b)	1.25	1.25
Twist direction	Z	Z
Twists per 10 cm	65.59	85.99

Knitted fabrics

Plain stitch fabrics were made from two yak wool folded yarns of 20.83×2 tex and 16.67×2 tex by a STOLL Flat Knitting Machine CMS530, in which a single strand of the 20.83×2 tex yarns and double strands of the 16.67×2 tex yarns were used for knitting, respectively. The latter could not stand the processing tension if single strand feeding was adopted. Then the basic physical properties of yak wool knitted fabrics such as density, loop length and thickness were examined. A thickness tester - YG141 was employed to test the fabric thickness at a counterweight of 100cN. Based on the GB/T3923.1-1997 standard, the tensile strength was tested by an electronic fabric strength tester - YG026 at a speed of 100 mm/min. According to the GB11048-1989 standard, a heat retention tester - YG606D was used for warmth retention tests under standard conditions (65 ± 2% RH), with the temperature set at 36 °C, a preheating time of 12 min and a sample size of 30 × 30 cm. Based on Standard GB/T5453-1997, a digital permeability tester - YG461E was used to test fabric permeability at a pressure difference of 100 Pa, for a testing area of 20 cm^2. Pilling tests were performed by a fabric pilling tester - YG502 at a pressure of 290 cN and for pilling times of 600, based on the GB/T 4802.1-2008 standard.

The knitted fabrics made from two yak wool folded yarns of 20.83×2 tex and 16.67×2 tex spun by the CCS and ring spinning were employed for wearability tests. Their basic physical properties are shown in ***Table 5***. Generally the density contrast coefficient (P_A/P_B) for the single knit fabric holds a range of 0.6 - 0.8. All knitted fabrics made from the yak wool yarns met the requirements. Furthermore the thickness and weight of the knitted fabrics made from yak wool yarns spun by the CCS were smaller than those of the knitted fabrics made by ring spinning. The possible reason was that the hairiness of the yak wool yarns spun by the CCS was reduced, especially the long harmful hairiness (≥ 3 mm).

The tensile strength of yak wool knitted fabrics is shown in ***Table 6***, from which it is easy to see that all the kinds of fabrics show higher tensile strength and lower

Table 2. *Basic physico-mechanical parameters of single and two folded yak wool yarns.*

Spinning method	Linear density of yarns	Breaking force, cN	Elongation at break, %	Tenacity, cN/tex	Yarn twists, t.p.m
CCS	20.83 tex	95.75	7.61	4.60	624.52
	20.83×2 tex	248.95	4.19	5.97	323.21
	16.67 tex	81.12	5.01	4.86	843.67
	16.67×2 tex	201.21	7.40	6.02	391.34
Ring spinning	20.83 tex	83.71	6.82	4.02	638.68
	20.83×2 tex	218.65	4.72	5.25	342.76
	16.67 tex	68.84	5.03	4.12	861.27
	16.67×2 tex	180.20	8.10	5.40	403.54

Table 3. *Evenness of single and two folded yak wool yarns.*

Spinning method	Linear density of yarns	CV, %	-50% thin/km	+50% thick/km	+200% neps/km
CCS	20.83 tex	14.51	24	32	15
	20.83×2 tex	8.42	0	10	5
	16.67 tex	15.76	60	80	75
	16.67×2 tex	9.64	3	26	24
Ring spinning	20.83 tex	16.12	60	95	115
	20.83×2 tex	10.23	2	31	38
	16.67 tex	17.84	210	225	380
	16.67×2 tex	12.42	9	62	71

Table 4. *Hairiness of single and two folded yak wool yarns.*

Spinning method	Linear density of yarns	1 mm	2 mm	≥3 mm
CCS	20.83 tex	1258.9	487.0	243.1
	20.83×2 tex	965.0	289.8	181.4
	16.67 tex	959.7	332.2	151.9
	16.67×2 tex	879.6	230.9	134.3
Ring spinning	20.83 tex	1472.1	525.6	602.4
	20.83×2 tex	1296.3	328.7	409.6
	16.67 tex	1097.5	368.4	497.6
	16.67×2 tex	867.8	254.1	323.2

Table 5. *Basic physical properties of yak wool knitted fabrics.*

Fabric type		Density			Density contrast coefficient	Loop length, mm	Weight, g/m^2	Average thickness, mm
		Np	P_A/5 cm	P_B/5 cm				
CCS	20.83×2 tex	11.5	36.5	50	0.73	5.4	121.61	0.48
	16.67×2 tex		38.5		0.77	4.7	229.22	0.77
Ring spinning	20.83×2 tex		36.5		0.73	5.4	122.93	0.48
	16.67×2 tex		38.5		0.77	4.7	230.04	0.78

Table 6. *Tensile strength and elongation at break of yak wool knitted fabrics.*

Fabric type		Warp-wise strength, N	Warp-wise elongation, mm	Weft-wise strength, N	Weft-wise elongation, mm
CCS	20.83×2 tex	290.5	125.5	172.5	221.1
	16.67×2 tex	308.3	126.2	209.0	210.1
Ring Spinning	20.83×2 tex	253.4	119.7	152.5	218.3
	16.67×2 tex	260.7	120.4	186.8	205.9

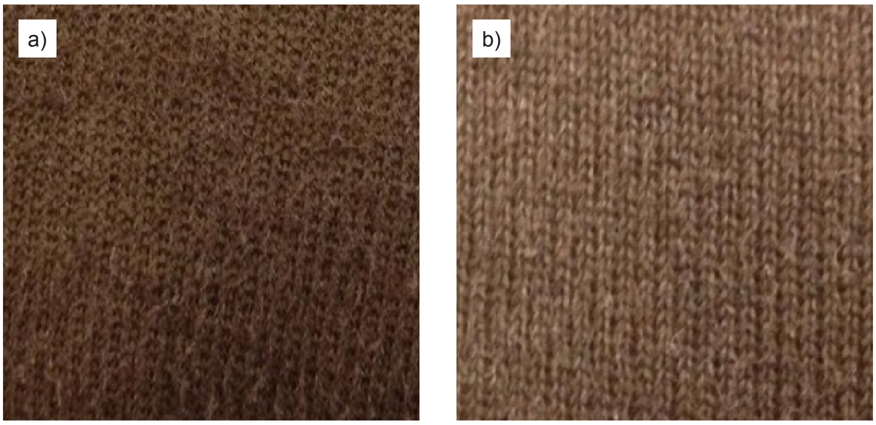

Figure 7. *Yak wool knitted fabrics after pilling; a) 20.83×2 tex, b) 16.67×2 tex.*

Table 7. *Pilling properties of yak wool knitted fabrics.*

Spinning method	20.83×2 tex	16.67×2 tex
CCS	3.0	3.5
Ring spinning	2.5	3.0

Table 8. *Warmth retention of yak wool knitted fabrics.*

Fabric type		Warmth retention rate, %	Heat transfer coefficient, W/m²·C	CLO value
CCS	20.83×2 tex	14.68	77.14	0.08
	16.67×2 tex	30.21	36.40	0.18
Ring spinning	20.83×2 tex	13.78	83.36	0.07
	16.67×2 tex	29.31	39.24	0.15

Table 9. *Warmth retention comparison between yak wool and cashmere knitted fabrics.*

Fabric type		Warmth retention rate, %	Heat transfer coefficient, W/m²·C	CLO Value
Yak wool	8.33×2 tex	15.51	80.08	0.08
Cashmere		7.68	176.6	0.04

Table 10. Permeability of yak wool knitted fabrics (mL/cm².s).

Spinning method	20.83×2 tex	16.67×2 tex
CCS	3016.81	1291.54
Ring spinning	3267.42	1389.76

elongation at break warp-wise than weft-wise. The fabrics made from 16.67×2 tex yak wool yarns spun by the CCS maintained higher tensile strength in both directions than those of 20.83×2 tex, because double strand feeding, instead of single strand feeding, was employed to produce the former type of fabrics, leading to an increase in fabric thickness. Furthermore the tensile strength of the yak wool knitted fabrics made from yarns spun by ring spinning were over 12% lower than that made by the CCS, which was because the fibres were less cohesive and more non-directional in the common ring spinning.

The pilling properties can be divided into 5 grades according to the GB/T 4802.1-2008 standard. The lower the grade of a fabric acquired, the worse pilling property it had. The pilling properties of yak wool knitted fabrics are shown in ***Table 7***, and the corresponding yak wool knitted fabrics made from yarns spun by the CCS after pilling are given in ***Figure 7***. It is easy to see that the anti-pilling of the knitted fabrics made from yarns of 20.83×2 tex was a little weaker than that of the knitted fabrics made from yarns of 16.67×2tex. Meanwhile, by using the CCS, the pilling properties of the corresponding yak wool knitted fabrics were improved when compared with those prepared by ring spinning.

The warmth retention of yak wool knitted fabrics was closely related to the shapes of the fibres. Medullary cavities and loose medulla layers could be found in yak wool fibres, with still air in them. Air itself is a poor conductor of heat, leading to the good heat preservation of yak wool. The fabrics made from yak wool yarns of 20.83×2 tex and 16.67×2 tex were evaluated by means of the warmth retention rate, heat transfer coefficient and CLO value (a CLO value of 1 means the tester maintained his/her average body surface temperature at 33 °C and a basal metabolism of 58.15 W/m² when the room temperature was 21 °C, relative humidity - less than 50%, and air velocity - more than 10 cm/s), which were all related to the heat dissipating capacity of the samples tested. The test results are shown in ***Table 8***, from which it can be seen that the fabrics made from yak wool yarns of 16.67×2 tex had a physical strand fineness from 33.33 tex to 66.66 tex. As a consequence, the opening percentage of the former fabrics was lower than that at 20.83×2 tex based on the same knitting density. As a result, the fabrics made from yak wool yarns of 16.67×2 tex obtained a tighter structure and higher efficiency to prevent heat loss. Meanwhile, when compared with the knitted fabrics made by ring spinning, the warmth retention of the knitted fabrics made by the CCS were a little higher.

Additionally it was reported that yak wool with the same fibre fineness as cashmere generally maintained 15% higher warmness [19]. Therefore a comparison between yak wool and commercial cashmere was made, shown in ***Table 9***. Generally cashmere products with high counts were of high commercial value. In this test, fabrics made from cashmere yarns of 8.33×2 tex were employed to compare with those made from yak wool yarns at the same count. The results showed that the high count yak wool fabrics gave a higher warmth retention rate and CLO value as well as a lower heat transfer coefficient than those of cashmere, which indicated that the heat retention of yak wool was about two times higher than that of cashmere.

The permeability of fabrics made from yak wool yarns of 20.83×2 tex and 16.67×2 tex is shown in ***Table 10***, from which differences can be seen between the two kinds of fabrics. Usually better warmth retention shows a stronger ability to hold still air, leading to better permeability. However, when compared with the knitted fabrics made by ring spinning, the permeability of the knitted fabrics made from yak wool yarns spun by the CCS decreased. The possible reason was that the long harmful hairiness (≥ 3 mm) of the yak wool yarns spun by ring spinning was more than that of yarns spun by the CCS, which made the fabrics bulkier.

Conclusions

Yak wool achieved excellent physical properties and inexpensive prices. However, conventional yak wool yarns can only be used for low end products due to its low count, which generally does not exceed 20.83tex due to the larger fibre dispersion and stiffness. In order to take full advantage of this unique material, a kind of roller-type compact spinning system - CCS was employed to produce high count yak wool yarns. The qualities of the yarns such as tensile properties, evenness and hairiness were firstly tested and compared with those spun by common ring spinning. Then corresponding yak wool knitted fabrics were made to test the wearability, which could further evaluate the effects of the CCS. The results showed that the CCS provided a way to produce high quality yak wool yarns with high counts. Additionally better heat retention of yak wool than that of cashmere was obtained, indicating a possibility to use yak wool as a supplement to cashmere.

Acknowledgements

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