Review

Textile Research Journal
Textile Research Journal
2015, Vol. 85(2) 211–224

DOI: 10.1177/0040517514538692
trj.sagepub.com
SAGE

Recent research and developments on yarn hairiness

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Abstract
Hairiness is an important quality parameter of spun yarns. It not only affects the quality of yarns, but also the weaving and knitting performance of yarns as well as the quality of the resultant fabrics. Various developments regarding yarn hairiness have been reported in the last decade. These cover aspects such as hairiness measurement, modeling, simulation, spinning modifications and post spinning treatments to reduce hairiness. This study is an attempt to critically review all significant recent developments regarding yarn hairiness. Further possibilities of research and future work are also briefly discussed.

Keywords
yarn hairiness, hairiness measurement, hairiness modeling, yarn spinning

Yarn hairiness is a critical yarn quality parameter. There has been significant interest in minimizing yarn hairiness to improve both yarn and fabric quality. Various methods of hairiness testing have been developed and evaluated. Attempts to model and predict yarn hairiness with different techniques have also been made over the last few years. This study is an effort to continue the series of reviews on yarn hairiness previously conducted by Barella and Barella and Manich.[1–4] The last review on this topic was published by Barella and Manich in 2002 with a focus on various improvements in yarn hairiness measurement, development of new spinning systems, hairiness reducing mechanisms, and post-spinning processes affected by yarn hairiness.[4] Since then, tremendous progress has been made in the field of yarn hairiness, ranging from modified spinning systems to applications of advanced modeling and measurement techniques to precisely determine true yarn hairiness.

Over 600 research studies directly or indirectly related to yarn hairiness have been reported in the last decade (Figure 1), from which at least 125 are directly focused on yarn hairiness. Even long-established theories on the fundamental characteristics of yarn hairiness are now challenged by new experimental evidence. It is now opportune to provide another update on yarn hairiness. This review covers recent information on developments in spinning to reduce yarn hairiness, post spinning mechanisms that contribute to hairiness reduction, application of advanced modeling techniques, i.e. neural networks and fuzzy logics for predicting hairiness, digital image processing, and signal processing for measurement of yarn hairiness and the effects of various material and processing parameters on yarn hairiness.

Yarn hairiness measurement

Two main instruments based on different working principles are in commercial use. One works through a sensor array that measures the length of protruding fibers from the yarn core (up to 25 mm distance) and categorizes them by length. The second method works through a light source incident on the yarn core, and the amount of light scattered by the protruding fibers is used to work out a hairiness index value for the yarn.[5,6]

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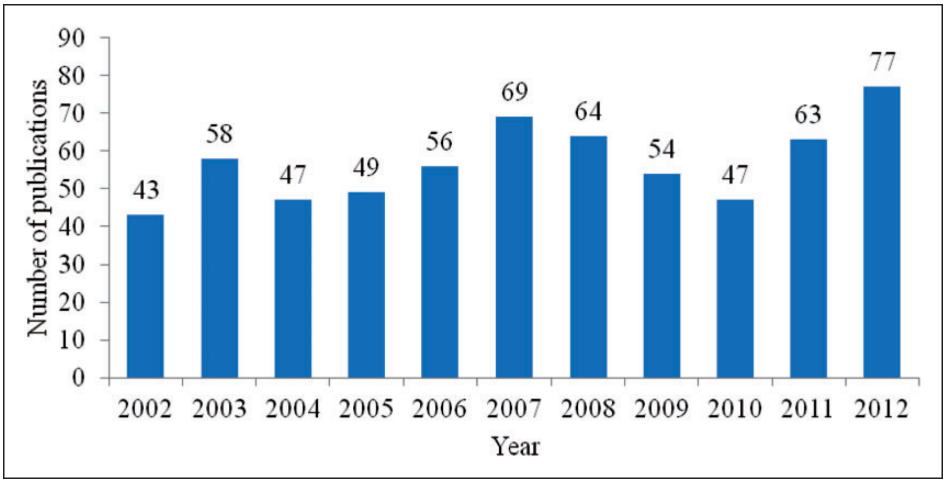

Figure 1. Publications per year that have directly or indirectly addressed yarn hairiness.

Novel solutions proposed for yarn hairiness measurement are largely based on digital image processing because of its ability to provide an intelligent vision system closely resembled to the human eye. Yarn hairiness measurement by means of signal processing is also reported by several researchers, which is discussed in subsequent sections.

Applications of image processing

Various applications of image processing in textiles, ranging from fiber characterization to end product serviceability evaluation, are discussed in a detailed review by Behera.[7] Majumdar reported applications of soft computing techniques in the textile industry and highlighted some developments associated with image processing techniques.[8] Utilizing image processing techniques, Kuzański et al. authored a series of research papers about appropriate hardware selection and software development for the measurement of yarn hairiness.[9–16] Images of yarns are captured by means of a high speed camera in the presence of back lit illumination and yarn transport system. In further research, Kuzański et al. explained the computer algorithm used to process the yarn images already captured.[16,17] The algorithm was capable of simultaneously identifying the number of hairs and hair length.

Ozkaya et al. investigated the possibility of application of image processing for the characterization of spun yarns.[18–21] Firstly the effect of different types of illumination on yarn imaging was examined. It was found that back lit illumination is best for visualizing the structural details of the yarn core. The same authors processed yarn images for hairiness measurement and introduced a new parameter called HDDP (Hairiness density distribution profile), which represents both the number of hairs and their length. Guha et al. also reported an image processing algorithm for yarn hairiness measurement.[22] The focus of their research was to measure the true or intrinsic yarn hairiness including those fibers that are entangled with each other. The algorithm successfully measured the length and number of hairs. A possible drawback in this method is very small scanning segments of yarns which might not give a true picture of yarn hairiness. Nevertheless the concept of true hairiness measurement is an important one.

Researchers from the Technical University of Lodz proposed an algorithm for extraction of the yarn core from a digital image, based on a graph cut method.[23,24] Chimeh et al. reported an approach for determining yarn hairiness using digital image processing as it plays a vital role in determining bulkiness of air textured yarns.[25] Wang et al. wrote a computer algorithm that was able to process the digital images of yarns.[26] A comparison with microscopic analysis, electrostatic measurement and optical methods showed that their method of hairiness measurement had improved measurement accuracy.

Yuvaraj and Nayar proposed a customized method of yarn hairiness measurement, which utilized an image processing algorithm. They also discussed the application of high voltage to erect the hairs from the yarn core during imaging.[27] This technique can help in untangling the hairs from the core and give a better estimate of the hairiness profile of yarn. The commercial feasibility of this method is not yet known.

Applications of sensors and signal processing

Other than image processing, some electronic sensor based systems were also suggested for yarn hairiness measurement by Carvalho et al.[28–37] The hardware consisted of lenses, photodiodes, optical filter and diaphragm. The yarn sample after illumination with a helium neon laser beam was sensed by means of photodiodes and the digital signals were processed in LabView software. They also experimented with CMOS line arrays for sensing hairiness. However, the poor cost-effectiveness of the solution may hinder its commercial feasibility. Anand et al. studied the light beam after passing through a yarn sample containing both polarized and depolarized components which retained the information about yarn hairiness intensity.[38] It was noted that installing the appropriate polarizers in the path of the light beam propagating towards the electronic detector can significantly improve the hair detection by the sensor hence enhancing the overall efficiency of the instrument.

Developments in existing hairiness measurement systems

The commonly used commercial hairiness testing devices are based on two principles, i.e. (i) arrays of sensors measuring the length of fibers protruding from the yarn core and (ii) detecting light scattered off the yarn core and calculating a hairiness index. The Uster tester (with a hairiness module) is a widely used testing instrument that works on the light scattering principle for the measurement of yarn hairiness. In the recent model (Uster Tester 5) the testing speed has been boosted from 400 m/min to 800 m/min, but the same testing principle is used.[5]

The well-known Zweigle hairiness tester works on the sensor array principle for hairiness testing and is now owned by Uster, with its recent model HL400 branded as Uster Zweigle hairiness tester. Yarn testing speed has been increased from a previous 50 m/min to 400 m/min in this model. The length groups have been reduced to 7, with hair length up to 10 mm rather than the 25 mm of previous models. The reason may be the emphasis on the S3 value, which is the total number of hairs with a length of 3 mm or above.[6] It is claimed by the manufacturer that results from the new and old instruments are comparable. This claim warrants further examination since yarn testing speed is known to affect yarn hairiness results.[39–42] This aspect is further discussed in the following section. Other notable hairiness instruments include SDL hairiness tester, Lawson Hemphill tester, and Keisokki Laserspot tester.[43–45]

Limitations of existing hairiness measurement systems

A well-established limitation of the hairiness measurement system is the effect of testing speed on yarn hairiness results. Wang et al. focused on this issue and discussed the differences in friction and air drag at different test speeds.[39–42,46] Serious limitations of sensor array based instruments reported by Ozkaya et al. were the effects of sensor resolution, determination of zero reference point on the instrument and signal threshold level on hairiness results.[21] The ability of the instrument to detect hair intersections normally decreases with a decrease in signal threshold level and similarly the determination of the zero reference point affects hairiness measurement.

Guha et al. pointed out the effect of orientation of the protruding hair on detection made by commercial instruments.[22] In most cases hairs are not straight or exactly perpendicular to the yarn core but can be entangled, wrapped around the core, twisted with each other and randomly oriented. This randomness in their structure does not allow conventional instruments to measure their true or intrinsic length. It is worth noting here that even the results of existing systems of hairiness measurement, working on different principles, cannot be correlated. A lot of work remains to be done on harmonization and standardization of hairiness testing.

The devices that measure yarn hairiness based on light scattering usually use a stoppage device to block the incident light so the sensor can detect the scattered signal. This stopping phenomenon can cause a loss of information, which may result in wrong measurement of yarn hairiness.[38] All types of existing hairiness measurement systems scan yarn samples in two dimensions for hairiness determination. Only those hairs that spread in front of the sensors will be considered during the measurement. Some hairs may be deflected during testing and only segments of these hairs protrude in front of the sensor. This will result in misclassification of hairs into wrong length groups. This issue certainly needs serious attention from the manufacturer's side. Hairs may be rubbed up during hairiness testing by stationary guides on the testing equipment and produce undesired air drag.[47] Replacing these stationary guides with moveable pulleys could improve the accuracy of hairiness test results.[41]

Recently, Haleem and Wang investigated the accuracy of measurement of existing hairiness systems by measuring the actual hairiness of different types of yarns using a tedious yet accurate manual method.[48] They straightened each hair and fixed it to a sheet of paper. The sheet was then scanned and analyzed to obtain true length and number of protruding hairs. The results revealed very significant discrepancies, not just in the number of hairs but also in the actual hair-length distribution profile. The hair numbers obtained from this manual method were much greater than that obtained from the hairiness meter, and the true hair-length distribution does not follow the well-known exponential decay. Most hairs range in length from

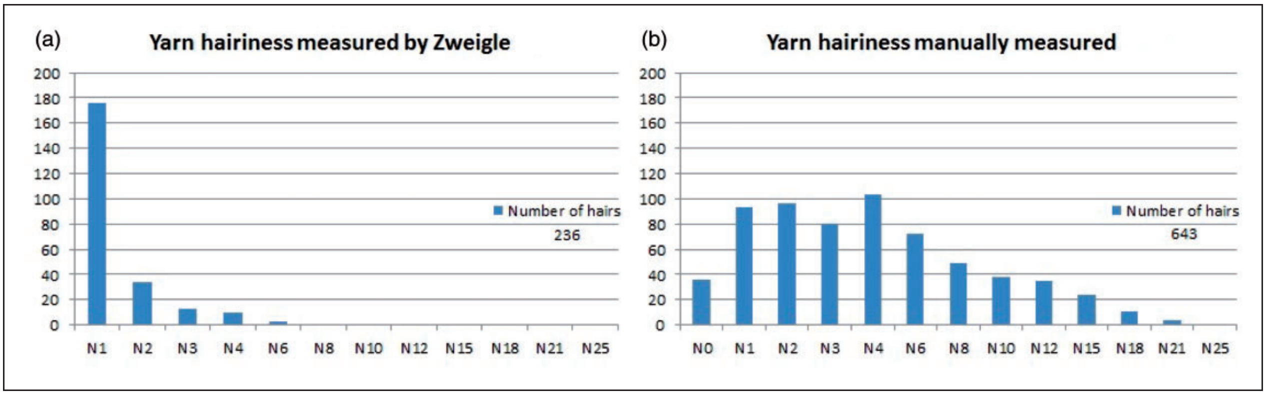

Figure 2. Comparison between the results of 50 tex cotton rotor yarn from Zweigle hairiness tester and manual method.[48]

1–12 mm and then hair frequency decreases gradually up to a length of around 25 mm. A comparison is given in Figure 2 between the histograms obtained from a Zweigle hairiness meter and the manual method.

Modeling and predicting yarn hairiness

Advancements in modeling and simulation techniques have allowed quite accurate prediction of yarn properties from fiber and processing parameters. Jackowska-Strumiłło et al. developed separate artificial neural networks using various quality parameters,[49] including yarn hairiness, for flax/cotton blended spun yarns. Predicted values from the neural model showed good agreement with actual values. It was further observed that finer yarns exhibited less hairiness as compared to coarser ones and the influence of blend ratio cannot be unambiguously determined on yarn hairiness. Similarly, in another study, a comparative analysis was made between regression, nonlinear regression, perceptron, and ADALINE networks for hairiness prediction.[50] The vital parameters affecting yarn hairiness were yarn linear density and cohesion of fibers in fed sliver.

Some other studies also reported hairiness models developed by taking various material and process related parameters as inputs.[51–53] Both regression analysis and neural networks were utilized for modeling yarn hairiness. However, neural models showed better results while predicting unseen data, pointing towards their ability to model even nonlinear relationships between variables, which is not possible by linear regression analysis. The logic is also supported by higher values of regression coefficient for neural networks as compared to linear regression. An important parameter affecting the performance of neural model is the size of training dataset. Comprehensive dataset with appropriate size can train a neural model to predict more efficiently while a limited dataset can significantly decreases its performance. Baykal et al. modeled hairiness of polyester cotton blended yarns by means of regression analysis taking blending ratio and yarn linear density as the input variables.[54] The observed effect of yarn linear density and blend ratio on hairiness agreed the established facts. Finer yarns possessed lower hairiness compared to coarser yarns. Increment in polyester content up to a certain limit in the blend reduced hairiness and later increased hairiness. Üreyen and Gürkan compared artificial neural network and statistics based regression models for predicting different yarn properties like unevenness and hairiness.[55] An important point here is inclusion of roving parameters in the input variables domain which was not done before. The neural networks performed better than regression analysis here as well indicating the superiority of neural networks due to their ability of understanding nonlinear relations. According to neural model, the decisive parameters that impact yarn hairiness are fiber length uniformity, fiber strength, and its elongation, while regression analysis points out fiber elongation and strength as major affecting parameters. Similarly, Khan et al. proposed two hairiness models based on multiple linear regression and artificial neural networks and compared the results with those obtained from the CSIRO Sirolan Yarnspec program.[56] Neural networks predicted the results closer to target values as compared to regression analysis. Through sensitivity analysis on developed model they found that yarn twist had the greatest effect on hairiness followed by other parameters like ring diameter, average fiber length, fiber diameter, and yarn count. Also, it was observed that relationships between fiber parameters and yarn properties are not perfectly linear.

An interesting publication by Majumdar et al. is worth mentioning here in which the most cost-effective fiber properties are predicted from the desired yarn

Table 1. Summary of neural network based models for predicting yarn hairiness

Researcher	Input nodes	Hidden neurons	Hidden layers	Data set/ observations	R^2 value	Comparison with other techniques	Platform
Jackowska-Strumillo et al.[49,50]	2	3	1	–	–	No	–
Beltran et al.[51]	15	–	1	280	98.2%	No	–
Babay et al.[52]	6	3	1	106	93.53%	Yes	–
Üreyen and Gürkan[55]	9	7	2	180	95.1%	Yes	Statistica
Khan et al.[56]	12	1	1	75	94%	Yes	–
Zhao[59–61]	5	5	1	16	–	No	Matlab
Zhao[59–61]	5	4	1	15	–	No	Matlab
Jackowska-Strumillo et al.[49,50]	2	3	1	108	–	No	–

properties by reversing the neural network.[57] In this case, yarn hairiness was selected as an input parameter along with other yarn parameters for choosing the appropriate raw material. The crucial parameters of bale selection, i.e. spinning consistency index and micronaire value of fiber for laydown in blow room, were predicted. The same authors proposed a neuro fuzzy model for predicting cotton yarn hairiness.[58] The analysis showed that two of the most critical parameters for predicting yarn hairiness are yarn count and fiber length. Hairiness decreased when yarn becomes finer and fiber length increased. Mature cotton fibers tended to produce less hairy yarns and short fiber content was not found significantly influencing hairiness. Zhao in his multiple papers reported models of cotton yarn hairiness developed through multi-layer perceptrons.[59–61] The hairiness of spun yarns was predicted from ring processing parameters, i.e. aperture of guide wire, nip gauge, spindle speed, and back draw time. Also using multi-layer perceptrons, the yarn hairiness after sizing and warping processes was predicted through the respective input parameters. However, no information was provided regarding the predictors and their respective influence on yarn hairiness.

Arain et al. investigated the quality parameters of rotor spun yarns based on parameters of rotor spinning,[62] i.e. speed of rotor and twist level. Rotor speed was found to have a nonlinear relationship with yarn hairiness with an increase in rotor speed at first improving then worsening hairiness. The possible reason for this quality deterioration is fiber disturbances due to high speed of rotor. Fattahi et al. modeled various yarn properties including yarn hairiness using a fuzzy least square regression technique.[63] They confirmed the well-established effects of short fiber content, fiber length and its fineness on yarn hairiness. It was noted that increase in short fiber index, yarn coarseness, and roving unevenness will increase yarn hairiness. Also increase in fiber strength and fineness will reduce hairiness. In a recent study, Haghighat et al. developed a series of neural networks for the prediction of hairiness of polyester/viscose yarns based on yarn properties and processing parameters.[64] However, no conclusions about the relative significance of parameters were presented. It was found that neural model performed well as compared to regression model because of higher R^2 value which is of course not the only metric of evaluating a model. Table 1 summarizes the above research on neural modeling of yarn hairiness with important network architecture parameters and information for comparison.

It can be deduced from the literature summarized above that two methods are mainly used when modeling yarn properties, and especially yarn hairiness. Artificial neural networks seem to have superior performance to classical regression analysis because of their ability of modeling nonlinear relationships among variables. However, a neural network is generally termed a 'black box' because of its inability to justify the results it produces. On the contrary, classical regression cannot effectively model the nonlinear relations, but the results are statistically understandable. Secondly, a range of variables from material and process domain were considered as inputs for model development. Selection of appropriate and significant variables is vital for developing an efficient model which can accurately predict the results from unseen datasets. Among discussed studies, the most common variables are fiber length and yarn linear density. Both of them are crucial factors that determine the hairiness intensity in the spun yarns. The findings agree with established facts regarding parameters influencing yarn hairiness.[1] However, incorporating other important variables into the model may lead to improved performance of the model.

Yarn spinning

Twisting of a fibrous strand is the basis of staple yarn manufacturing. In recent decades several new spinning systems have been introduced. These new spinning systems have resulted in significant improvements in yarn productivity, but not necessarily in yarn quality. Ring spinning remains the dominant system for high quality staple yarn production. In addition to high yarn quality, the success of ring spinning system lies in its ability to spin a wide range of fiber types into yarns of different linear densities, its easy maintenance and availability of technical expertise.[65]

Modifications in conventional spinning machines for hairiness reduction

As yarn hairiness is an important parameter of yarn quality modifications to processing and to conventional spinning machines have been investigated in terms of reducing yarn hairiness. Mirzaei et al. proposed a modification to carding to remove short fibers from the surface of the carding web.[66] Special perforated suction rollers were installed on a carding machine after the doffer for removal of short fibers. The yarns made from this system are called VCC (vacuum clean carded) yarns and exhibited significant improvements in quality over conventional carded yarns especially in terms of hairiness. However, there is no comparison made by the authors with conventional combed yarns, where short fibers are removed in combing. It would be interesting to see if VCC yarns can exhibit even superior quality than combed yarns. This idea may lead to elimination of lap formers and combers from the combed yarn spinning line.

Wang et al. reported a hairiness reduction technique by introducing a diagonal yarn path arrangement on conventional ring spinning machine by simply diverting the front roller delivery to the adjacent diagonal spindle on the right side.[67] This modification produced yarns with reduced hairiness due to skewing of the spinning triangle. Thilagavathi et al. studied different variants of diagonal spinning arrangements and also discussed different types of bottom rollers and spinning offsets that can reduce hairiness.[68,69] Wang et al. introduced the concept of Jetring spinning by incorporating an air jet into conventional ring spinning. This combination assisted the wrapping of protruding fibers into yarn core resulting in a significant decrease in yarn hairiness.[70]

Najar et al. developed a hybrid system of Solo–Siro spinning, and spun 100% wool yarns of different linear densities on the hybrid system as well as separately on the Solo and Siro spun systems.[71] An overall improvement in Solo–Siro spun yarns was noticed including a significant reduction in yarn hairiness. Nejad et al. proposed another hybrid mechanism by incorporating an air jet nozzle in the Sirospun spinning system.[72] The air nozzle wrapped the fibers around the yarn core and reduced hairiness by up to 40% compared to conventional yarns. Some further studies also reported developments regarding Siro Jet hybrid spinning systems and subsequent improvements in yarn quality.[73,74] Following the trend of hybrid spinning, Yilmaz and Usal reported a combination of compact and jet spinning.[75] Feng et al. studied the effect of different speed ratios by installing a false twisting assembly in the path of yarn on a conventional ring frame to modify the spinning triangle for hairiness reduction.[76]

Yazdi explored the effect of directed movement of fibers in the spinning triangle zone by using bottom rollers of various flute types, angles and directions.[77] Rollers with a 75° groove from both sides towards the center produced the least hairy yarns compared with other flute geometries but the result was sensitive to twist direction. In another study, the effects of parts of the winding section of a ring frame, e.g. thread guide eccentricity, spindle speed, diameter of balloon breaker, traveler weight, and humidity on hairiness of polyester viscose blended yarns are discussed.[78] Higher spindle speed, guide eccentricity (except in the forward direction), larger balloon diameter, lower traveler weight, and low humidity negatively influenced yarn hairiness. Hua et al. introduced a special jet nozzle that can be incorporated into the conventional ring spinning system in order to reduce the yarn hairiness by means of air whirling phenomena.[79] Xia et al. developed a contact surface next to the front roller nip at an approximate distance of 20 mm to rewrap the protruding fibers and reduce yarn hairiness.[80] The contact surface significantly reduced yarn hairiness but the evenness of the yarn was deteriorated. Another study focused on introduction of a rubbing surface arrangement in the drafting assembly to achieve better yarn quality but it worsened yarn evenness while improving yarn hairiness.[81]

Compact spinning systems

Compact spinning is perhaps the most remarkable spinning innovation of the last two decades. It is essentially a modified ring spinning system, which results in yarns of improved quality. Rieter is one of the largest manufacturers of spinning machines around the world. The latest compact spinning machine launched by Rieter is the K45 ComforSpin.[82] The compacting mechanism consists of suction elements including a perforated drum, air guide, suction slot and suction insert. Once the fibrous strand passes through the front delivery roller it gets compacted by means of air suction. The compacting of the fibrous strand before twist insertion results in reduced yarn hairiness and improved yarn tensile properties. Another innovation was introduced by Oerlikon Schlafhorst and is branded as Zinser

Modular Concept 351 for compact spinning.[83] The mechanism achieves fiber compaction by means of suction through a perforated apron that moves over the bottom delivery roller. The considerable benefits of this system are its ability to process a variety of raw materials and self-cleaning, which can protect the compacting elements from choking by dust particles and fiber.

Apart from compact systems that are built-in parts of modern ring frames, Suessen offers the EliTe® Compact Set-S attachment that can be mounted on the drafting system of almost any conventional ring frame as an add on.[84] It consists of a top roller, apron, perforated base plate, and suction system. The suction through the base plate condenses the fibrous strand, which then results in a compact yarn after twist insertion. An innovative yet simple solution for compacting the fibrous strand in the spinning triangle zone was introduced by Rotorcraft branded as Rocos.[85] This system, unlike the air suction based compacting methods, places a trumpet guide in front of an additional roller that mechanically condenses the fibers before twist insertion. The main benefit of the Rocos system is its simplicity and low cost but it does not create a significant improvement in yarn quality.

Analysis of yarn hairiness spun using different spinning systems

Yarns spun with different spinning techniques have different fiber configurations within the yarn structure. The fiber configurations of ring, rotor and friction spun yarns were observed in a study by introducing 1% tracer fibers in the sliver and mean fiber positions were calculated.[86] The existence of fibers near the core or periphery of yarn seemed to strongly influence the yarn hairiness. Rotor yarns possessed lower hairiness as compared to ring and friction spun yarns because fibers are majorly gathered around yarn center in rotor yarns. In friction spun yarns the fibers are lying around the periphery and they exhibited highest values of hairiness. Cheng et al. presented a comparison of ring spun and Solospun yarn hairiness. Solospun yarns showed relatively better hairiness which was explained on the basis of sub-strand formation at the spinning triangle region resulting in better trapping of fibers within the yarn core.[87] Cheng and Li investigated the properties of jet ring spun yarn and the effect of certain process parameters on yarn hairiness like twist and spinning speed.[88] Jet ring spun yarns showed better characteristics than conventional yarns because of the wrapping of protruding fibers due to jet action on the fibrous strand.

Zeng and Yu modeled the jet spinning nozzle by numerical modeling methods and analyzed various nozzle related parameters.[89–91] Yarn hairiness was reduced by introducing a jet into the path of fibers but it degraded yarn evenness mainly due to the concentrating fiber mass. Studies aimed at improving the nozzle design have been carried out by Rengasamy et al. who used a fluid dynamics based model of the nozzle.[92–98] Using the model, air pressure and distance of nozzle from the front roller were optimized for producing less hairy and more even yarns. The axial angles, internal diameter of nozzles, air velocity and angle of impact of air inside the nozzle were also studied and related to yarn properties. Subramanian et al. investigated the type of material of the jet spinning nozzle by experimenting with brass, aluminum and Teflon nozzles.[99] Multiple nozzles were installed in the yarn path, i.e. single, double, and triple nozzles, to observe whether there was an improvement in yarn properties. The least hairy yarns were achieved using a single brass nozzle, as multiple nozzles worsened yarn structure. Beltran et al. compared the hairiness and pilling performance of yarns spun from Solo spinning, conventional ring spinning, and jet wind processed yarns.[100] While Solo spun yarns exhibited minimum S3 value, jet wound yarns resulted in fabrics with better pilling performance.

Aghasian et al. studied the effect of polyester cotton blend ratio on yarn hairiness and found that increasing the cotton content increased yarn hairiness.[101] In another study, increasing polyester content in polyester cotton blended yarns reduced yarn hairiness.[102] Chen et al. investigated properties of yarn spun on embeddable and locatable spinning,[103] which is essentially a modified Sirospun or Sirofil system. Sawhney and Kimmel incorporated an air jet in the yarn path of a conventional ring frame to produce a tandem spinning system.[104] The key idea was to increase the ring frame production by partially substituting the twist insertion in yarns through air jet. The system practically increased the yarn production rate up to 50% in some cases. The utilization of air jet also improved the yarn properties specifically yarn hairiness by wrapping the protruding fibers around the yarn core.[105] Another spinning system named Rockwell electrostatic spinning method claimed better fiber control resulting in less hairy yarns, but it could not find much commercial success.[106]

The key factor of improvement in yarn quality parameters is incorporation or trapping of fibers inside the yarn strand.[107] Better incorporation will certainly reduce yarn hairiness by providing less chance for fibers to protrude from yarn structure. In conventional ring yarns, the fibers are arranged in form of helixes of multiple radii. During this arrangement, fibers sometimes get entangled, looped, or protruded from yarn structure resulting in partial incorporation within yarn structure and less contribution towards quality parameters. Different modifications in conventional spinning as discussed above, try to trap fibers inside the yarn structure in different ways. In Solo and Siro spinning methods, the variation in twist of the sub strands is responsible for locking fibers inside yarn.[108] In compact spinning systems, the basic idea of trapping fibers within yarn structure is to reduce the width of fibrous strand emerging from front delivery roller hence modifying the geometry of spinning triangle. Jet ring and jet wind mechanisms attempt to tuck in the open ends of the fibers protruding from yarn core by wrapping them through air jets.

Post spinning developments regarding yarn hairiness

Yarn passes through multiple machines after spinning in processes such as winding, sizing, warping, weaving, and desizing. Mechanical interaction of yarn leads to increased hairiness due to contact with rough surfaces and varying tensions being applied to the yarn. The hairs protruding from yarns may eventually lead to pilling of the fabric surface and poorer appearance.[100] Lang et al. investigated the post spinning increase in yarn hairiness during auto winding using a theoretical model.[109] They found the minimum fiber length and fiber metal friction level at which a fiber can be pulled out of the yarn core contributing to an increase in hairiness.

Rengasamy et al. investigated parameters of the nozzle used in the jet winding process to reduce yarn hairiness.[110] Experiments based on a Box-Behnken statistical design showed that the best hairiness results of 10 tex yarn were obtained with a nozzle of 45° axial angle, 2.2 mm internal diameter and winding speed of 800 m/min. Patnaik et al. studied the hairiness of viscose yarns spun on ring, rotor, air jet, and open end friction spinning systems with and without application of the jet wind process.[96] The results showed that hairiness for all four types of yarn was 16–30% lower for jet winding than conventional winding. The same authors also evaluated a hairiness reduction nozzle for polyester yarns.[98] It was found that the most important parameter in hairiness reduction by means of an air jet nozzle is the fiber fineness because different air pressure is required in the nozzle for different fineness of fibers and the optimum pressure is essential for effective hairiness reduction.

Ishtiaque et al. compared the before and after plying properties of conventional and compact yarns.[111] Initially, single compact and conventional yarns exhibited a great difference in hairiness but after plying, the difference was greatly reduced. However, in both cases compact yarns had reduced hairiness. Basu et al. proposed an artificial neural model for prediction of various fabric properties and observed the effect of yarn hairiness on bending length, kinetic frictional resistance, drape coefficient, and compressional energy of the fabric.[112] An increase in yarn hairiness seemed to increase bending length and kinetic frictional resistance while the opposite was found for compressional energy and drape coefficient of the fabric. Yao et al. predicted the yarn breakage rate at warping using neural networks as it is a critical evaluation criterion for yarn performance on a loom and can even lead to yarn rejection in severe cases.[113] Ghosh and Bhowmick studied the causes of excessive fly generation in the knitting shed and reported cone unwinding as the major cause.[114] More hairy yarns tend to generate more fluff in the unwinding zones. This finding is in agreement with previous studies that suggested a direct relationship between fiber fly generation and yarn hairiness.[115,116]

Apart from process parameters, fabric pilling is a serious concern that has its roots in yarn hairiness. In some recent studies, the effect of various parameters like fiber morphology, fiber characteristics, yarn twist, and spinning method were also correlated with hairiness and then with pilling propensity of the fabric.[117–119] Özdemir and Oğulata investigated the dyeing performance and color efficiency of yarns made from air vortex and rotor spinning.[120] Yarns spun on the air vortex system showed greater color efficiency and darker shades than rotor yarns because of the unique and better fiber alignment resulting in improved evenness and less hairiness.

Causes of yarn hairiness

Yarn hairiness is a necessary consequence of twisting finite length fibers into a yarn. However, the level of hairiness is affected by the properties of the raw material, yarn parameters, and processing parameters.

Causes related to raw material properties

Altaş and Kadoğlu presented a paper describing the relationship of yarn linear density and fiber properties to yarn hairiness.[121] Two different yarns were spun from fifteen different varieties of cotton while keeping all the process parameters constant. It was observed that yarn linear density had a significant effect on yarn hairiness and coarser yarns tended to be hairier than finer yarns because of the higher number of fibers in cross section. Fiber length and fineness were found to significantly affect the hairiness of finer yarns more than coarser yarns. Greater mean fiber length is associated with less hairy yarns and coarser fibers with more hairy yarns because of higher flexural and torsional rigidity. Fiber strength and elongation were found to be negatively correlated with yarn hairiness. An interesting and unusual finding was the effect of uniformity ratio, with increasing ratio associated with increased yarn hairiness. An increase in short fiber percentage increased yarn hairiness while trash content did not have a significant effect on hairiness.

Krifa and Ethridge examined the effect of fiber parameters on yarn hairiness for conventional and compact spinning using both Uster and Zweigle testers.[122] Yarns were spun from short and medium staple cotton on both systems. The testing results showed that yarn hairiness for short staple and non-uniform cotton was quite significantly reduced (up to 94%) by compact spinning but not for long staple fibers having better uniformity. Wang et al. highlighted the impact of fiber structure on physical properties of yarns typically hairiness of wool and cashmere yarns.[123] It was observed that the yarn hairiness is significantly affected by fiber curvature and they are inversely proportional to each other. Using more crimpy fiber in yarn spinning led to less hairy yarns for the same yarn count. More crimpy fibers tended to enhance internal fiber cohesion that kept the fibers compact and increased the fiber security during yarn spinning resulting in less hairy yarn.

It is important to mention here that raw material characteristics play a vital role in understanding the output parameters like hairiness irrespective of the spinning method under discussion. In a study, it was observed that harvesting techniques employed in cotton field significantly affected the yarn properties including hairiness.[124] The yarns spun from pick harvesting cotton exhibited low hairiness as compared to the ones spun from strip harvesting. The reason behind this is damage to fiber by intensive harvesting action which increased the short fiber content in the raw material. Krupincova studied the effect of various fiber characteristics on yarn properties particularly yarn hairiness.[125] It was noted that influence of most of the fiber characteristics was not significant on yarn properties except fiber length. Longer fibers tended to produce not only less hairy yarns but also improved other yarn properties. Also coarser yarns exhibited more hairiness as compared to finer yarns. In another study, the effect of fiber parameters on yarn hairiness was investigated using a combination of classic statistical modeling and Monte Carlo techniques.[126] It was observed that yarn count (tex), fiber length, maturity, and trash all have negative correlation with yarn hairiness. However, yarn twist, fiber micronaire, strength, length uniformity, and elongation posed a positive correlation with hairiness.

Causes related to process parameters

Kumar et al. studied the effect of various process parameters including lap hank fineness and drafting on carded cotton rotor, ring and air jet yarn quality.[127] The hairiness of ring yarns were found to be somewhere between rotor and air jet yarns. Higher draft on ring and air jet spinning machines while lower draft on rotor increased yarn hairiness. It was also observed that increased draft on card and speed frame significantly reduced yarn hairiness. Another study explored the effects of spinning preparatory process parameters on yarn quality like draw frame delivery speed, coiler diameter and draft on the card machine.[128] Statistical analysis revealed that coiler diameter of card and delivery speeds of draw frame are negatively correlated with yarn hairiness while increasing draft in carding served to increase yarn hairiness which agrees with previous findings.[117]

Wang et al. analyzed the reasons of hairiness generation right from its origin,[129] i.e. spinning triangle. A CCD camera was mounted on ring frame to capture images of spinning triangle at low delivery rate to understand the formation of yarn hairiness. It was observed that pre twisting of fibers at spinning triangle played a key role regarding hairiness generation. For example, the right side of spinning triangle possessed a better control on protruding fibers as compared to the left side while spinning a Z-twist yarn. Also short and poorly aligned fibers tend to produce hairs and loops respectively because of relatively less control in the main fiber stream. Tyagi et al.,[130–133] while determining the effect of process parameters on hand related characteristics and comfort parameters of fabrics, noticed the effect of draft ratio on the yarn hairiness. The yarns were spun with varying twist levels, draft ratios and spinning speeds. A significant reduction in hairiness was observed with increase in twist and spindle speed and decrease in the spinning draft ratio. Kakvan et al. found the effect of filament draw ratio and positioning on various core spun yarn characteristics particularly yarn hairiness.[134] They observed the best position of filament is in the center of the roving and a medium level of drawing of the filament is suitable for spinning less hairy core spun yarns as it better entraps the fibers and incorporates them into the yarn core. In an attempt to investigate the influencing parameters on core spun yarns hairiness, Pourahmad and Johari presented a comparison of conventional ring, Solo, and Siro core spun yarns made from acrylic sheath and nylon core filament.[135] Filament pretension, spinning system, and feeding position of filament into sheath fibers were studied.

A relationship between yarn evenness and hairiness was presented by Xia et al. through a mathematical model.[136] It was observed with imaging aids that thick places in the yarn structure held less protruding fiber mass while more hairiness was found around thin sections of yarn. This observation was further confirmed with fluorescence microscopy. Altaş and Kadoğlu investigated the effect of spinning parameters on polyester viscose yarn properties on DREF-3 friction spinning system.[137] Air suction pressure was found to be negatively influencing yarn hairiness as more suction resulted in less hairy yarns. Similarly an increase in core/sheath ratio reduced yarn hairiness because of fewer fibers in the sheath; however, increased drum speed tended to produce more hairy yarns. Erol and Sagbas studied the effect of spindle speed, twist level and weight of traveler on ring spun yarn properties especially yarn hairiness through a central composite design based experimental plan.[138] Keeping the spindle speed and twist level on the lower side and increasing the traveler weight resulted in reduced yarn hairiness without worsening other properties like strength. Usta and Canoglu explored the effect of ring traveler weight and its coating on the properties of ring spun yarns made from cotton and acrylic.[139] Their findings supported the previous conclusions of using heavier travelers for less hairy yarns. The heavier travelers produced more tension in yarns resulting in less hairiness. The travelers which were polished and were coated with different materials, tended to give lower yarn hairiness.

Conclusions

Yarn hairiness is an important quality parameter of yarns and has vital importance for yarn performance in further processing and for end product performance. Accurate measurement of yarn hairiness is necessary for appropriate quality control. Currently, two hairiness measurement methods based on either a linear array of optical sensors or light scattering principles are commercially in use. Several limitations with these systems raised the necessity of development of new solutions for yarn hairiness determination. Image and signal processing techniques have been investigated as effective and efficient means for evaluating this important yarn characteristic. Successful development of testing hardware and the design of intelligent algorithms has been reported but these solutions have not yet been commercialized. It can be anticipated that novel solutions for hairiness measurement will be available soon because of increasing awareness and demand for quality.

Appreciable efforts have been made in modeling yarn hairiness. Various models through statistical and artificial intelligence means were reported predicting the value of yarn hairiness from a wide range of process and material based parameters. The predictions of the models were claimed to be very good. Datasets of acceptable number of observations were utilized to train and validate the neural networks and regression equations. However, neural network based models gave better prediction of output variables than regression equations because of their ability to learn from data patterns and nonlinear fitting of data. Appropriate applications of well-designed models in the spinning industry can serve as a decision support system to achieve high end quality products.

Compact spinning has been a popular recent innovation for reducing yarn hairiness. Different compact spinning systems have been developed by leading textile machinery manufacturers and successfully commercialized. Almost all types of compacting assemblies have resulted in great improvements in yarn properties including strength and elongation and reduced hairiness. They also improved the productivity of spinning process by effective utilization of raw material. Fabrics made from compact spun yarns, whether knitted or woven, exhibited better quality parameters especially pilling performance than fabrics made from conventional yarns. In spite of all these benefits, compact spinning systems often demand additional high capital investment. Their running cost is also higher than conventional ring spinning systems because of additional energy and maintenance requirements of the compacting elements. Considering this problem, some modifications to conventional ring spinning machines have been reported as well which significantly improved yarn properties including hairiness without any or little extra cost. Such developments include a diagonal yarn path arrangement, combination of Siro and Solo spinning systems, combination of jet spinning and Siro spinning systems, introduction of a false twisting assembly above the yarn guide, hybridization of compact and jet spinning systems and application of specially designed grooved bottom rollers for directed movement of fibers in the spinning triangle.

With the introduction of the jet spinning and jet winding processes specifically designed for reduction of yarn hairiness, efforts were made to improve the performance of air nozzles used for this purpose. Multiple studies have been presented about the effect of nozzle diameter, axial angle, air pressure, nozzle material and nozzle placement on the reduction in yarn hairiness using computational fluid dynamics based simulations. Post spinning advancements regarding yarn hairiness have also been a focus and there have been improvements in the winding process to reduce yarn hairiness and plying and doubling can also affect yarn hairiness.

Parameters that are directly responsible for increases in yarn hairiness are also summarized in two categories of process and material origins. Spinning process variables that are somehow correlated with yarn hairiness and earlier process parameters are reported for regular as well as core spun yarns and, if properly controlled, can give significantly lower yarn hairiness.

Fiber structure, length, fineness, uniformity ratio and short fiber content are the material based parameters that must be considered before spinning a yarn in order to yield better hairiness values.

In the context of this study and comprehensive review of recent developments in improving yarn hairiness, it is essential to mention some suggestions and possible future work in this area. Measurement of true yarn hairiness is far from reality today because of limitations in existing measurement systems. It is necessary to utilize the intelligent solutions like image and signal processing in combination with promising hardware designs to measure the true hairiness of spun yarns on a commercial scale. Reducing yarn hairiness by means of compact spinning might be an expensive solution for some companies, but simple modifications to existing machines or even to the fibers themselves may also produce yarns with improved quality. In addition to ring spinning, it is important to study other spinning systems with the latest available techniques and technology to further improve them for production of less hairy and highly even yarns.

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