ANALYSIS OF FORMATION OF MASS IRREGULARITY IN DRAFTING DEVICE DURING YARN SPINNING FROM SLIVER

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Abstract: *This work deals with an analysis of formation of mass irregularity of fibrous product in a drafting arrangement of air-jet spinning machine. Sliver is supplied into the machine and attenuated in four-line double-apron drafting arrangements before formation into yarn. There, the total draft is realized within three zones: infeed draft, intermediate draft and main draft. In the work, the components of mass irregularity (limiting, systematic, additional and systematic developed from latent (immeasurable) irregularity), which form the structure of total mass irregularity of fiber strand in the output from the drafting unit, were defined. Transformation of mass irregularity of fibrous assembly by this drafting device was theoretically analyzed. The theoretical analysis of machine irregularity was realized too. Within the experiment, 100% Tencel yarns of count 23 tex were spun from the sliver of three various linear densities using the Rieter air-jet spinning machine J20. Three levels of intermediate draft ratio were also set. Proportionally to it, the level of main draft ratio was changed, while the both infeed draft ratio and other spinning parameters were kept constant. Sliver and yarn mass irregularity as well as number of yarn faults were measured and analyzed, machine irregularity was calculated. The results showed that the lowest value of yarn mass irregularity is achieved when the sliver with higher linear density in combination with the lowest level of intermediate draft ratio (both from the observed range) is used for air-jet yarn production. It confirmed the theoretical analysis that draft ratios in infeed and intermediate drafting zone has more significant importance for air-jet yarn mass irregularity compared to the level of main draft ratio. Sliver mass irregularity is also very important factor for total yarn mass irregularity. Similar results were also recorded for number of yarn faults (especially for thin places (-40%)).*

Key words: *Air-jet spinning, drafting, main draft ratio, intermediate draft ratio, yarn mass irregularity, components of yarn mass irregularity.*

1 INTRODUCTION

In the technology of staple spun yarn production, the draft is used for attenuation of supply fibrous product, fiber straightening and their aligning to a parallel position. The draft occurs usually in the drafting mechanism between pairs of roller, rotating at different speed. The principle of drawing is that fibers move relatively to each other to be distributed over a longer length of the product. It is generally known that drafting processes have significant effect on the yarn mass unevenness. Usually, higher draft ratio leads to higher total yarn irregularity and number of faults. A lot of research papers deal with analyses of drafting process and with a study of effect of drafting of yarn mass irregularity. Authors predominantly study the movement of fibers in the drafting zone, for example, in works [1, 2], or analyze drafting forces, for example, in works [3, 4]. The irregularity added by an apron drafting system on the ring spinning frame was studied in work [5]. During spinning from sliver, especially in the case of unconventional spinning systems such as a rotor spinning system, but also in the case of other spinning systems where a high-drafting device is used for given attenuation, it is necessary to apply a high draft ratio. The air-jet spinning system belongs to them. The process of forming the yarn on the air-jet spinning system comprises attenuation of supply sliver by the draft in the four-roller drafting device equipped with two aprons in the main drafting zone. Consequently, thin fibers strand is transformed into the yarn by means of vortex air in the nozzle houses [6]. Thanks to it, air-jet yarns are featured by a different, specific structure (so called fasciated yarn). The yarn consists of a core where fibers are parallel and without any twist, and of wrapper fibers twisted around the core. Although there are many research works focused on the air-jet yarns, they primarily deal with the influence of technological variables on the properties of air-jet yarns produced on Murata Vortex Spinning Machine (MVS) (for example [7-10]) or simulation of air flow field in the MVS nozzle chamber (for example [11]). In the year 2009, Rieter Company introduced also their air-jet spinning machine. It differs from the MVS by the machine concept, the nozzle geometry and fiber guide in the front of spinning tip placed in the nozzle house. Except for several works dealing with prediction of air-jet yarn tenacity [12], properties of plied air-jet yarn [13] or numerical simulation [14], there is a lack of research work about Rieter air-jet spinning system today. The effect of draft ratio on the properties of vortex spun yarn was investigated only in work [10]. Authors measured mass irregularity of yarn (15 tex) made of 100% VS fibres using the Murata Vortex spinning system. They spun set of yarns from slivers of three counts using two levels of intermediate draft ratio (2.3; 2.5). During results analysis, the authors limit on a two-way analysis of variance and statement that yarn samples spun with the lowest main draft ratio with highest used intermediate draft level achieved the worst irregularity. They concluded that it is a reason of out of optimum level of intermediate draft. However, for determination of the conditions ensuring optimal course of drafting process it is important to know the effect of the draft on the structure of mass unevenness. Therefore, the subject of our analysis is a high-drafting device (see Figure 1) used on the air-jet spinning machine. This device is characterized by three drafting zones that ensure the required total draft. Namely, it is a zone of infeed draft *P0*, a zone of intermediate draft *P1* and a zone of main draft *P2*. The infeed drafting zone and intermediate drafting zone consist in drafting rollers whereas in the main drafting zone also a pair of aprons controls fibers. In our case, the infeed draft ratio is constant for given fibrous material, the intermediate draft as well as the main draft is changed according to the experiment. Because of this, we assume that finally the main drafting zone and intermediate drafting zone form the total yarn mass irregularity. These zones will be a subject of theoretical analysis in the terms of their influence on the total mass unevenness of air-jet yarn. The analysis will be carried out also experimentally. At the same time, more general piece of knowledge about transformation of mass irregularity of linear fibrous product exposed to drafting processes in the given drafting device will be applied.

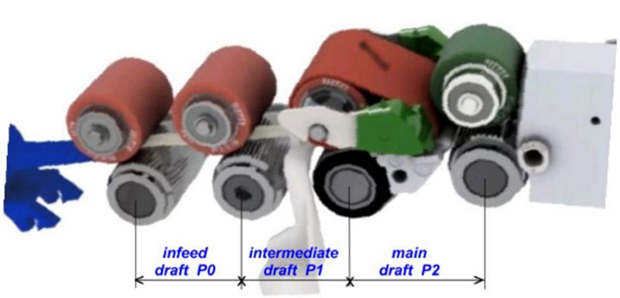

Figure 1 Scheme of drafting device of air-jet spinning machine (adapted and reproduced [17])

2 THEORY OF CHANGES OF MASS IRREGULARITY DUE TO DRAFT

2.1 General rules

The analysis of mass irregularity formation is performed on the basis of the laws of variation phenomena in random process. The total variation in the mass of short lengths of final product in a yarn manufacture can be regarded as the sum of the variations of individual components of mass irregularity (see equation (1)).

$$CV^2 = \sum_{i=1}^{k} CV_i^2 \tag{1}$$

where CV_i is ith component of yarn square mass irregularity.

We consider following CV_i components [15, 16]:

CV_I - square limiting irregularity. It is determined by a random distribution of number of fibers in the sliver or yarn cross - sections. For better clarity, this component will be further referred as CV_{lim}.

CV_{II} - systematic square mass irregularity. It is caused by negative effects of technological stages before spinning system. For better clarity, this component will be further referred as CV_S. In the case of air jet spinning, CV_S includes also negative effect of infeed draft in the drafting arrangement of the air-jet spinning machine.

CV_{III} - additional square mass irregularity. It is induced only by the given technological stage (in our case by the spinning system). This component will be further referred as $CV_{P,}$

CV_{IV} - systematic square mass irregularity which is developed from a latent irregularity (immeasurable on very short lengths) due to drafting in given technological process (spinning). For better clarity, this component will be further referred as CV_{VS}.

We assume that the individual components of mass irregularity are mutually independent. As total variation in the mass of yarn short lengths we can use the parameter CV_m. It is a yarn total square mass irregularity obtained from Uster Tester and it will be further referred as CV_{yarn}. In our analysis, we start from above-mentioned components of mass irregularity. We determine the structure of mass irregularity of product in the input to the system and in the output from the system as well as resulting degree of mass irregularity using the effect of draft ratio and doubling (in general case) on the appropriate components of mass irregularity

2.2 Transformation rules of mass irregularity

Let us consider a general spinning system characterized by a certain draft *P* and doubling *D*. Due to different causes of the formation of individual components of total mass irregularity, the following expressions can be made:

$$CV_2^2 = CV_{lim2}^2 + CV_{S2}^2 + CV_P^2 + CV_{VS}^2 \tag{2}$$

and

$$CV_0^2 = CV_{lim0}^2 + CV_{S0}^2 \tag{3}$$

where quantities indexed by 0 express corresponding components of mass irregularity of fibrous product in the input into the spinning system and quantities marked by index 2 express corresponding components of mass irregularity in the output from the system.

Using the general transformation rules for limiting CV_{lim} and systematic CV_s square mass irregularity [15], we can express resulting total square mass irregularity of linear staple-spun product CV_2:

$$CV_2^2 = CV_{lim0}^2\left(\frac{P}{D}\right) + \frac{CV_{S0}^2}{D} + CV_P^2 + CV_{VS}^2 \tag{4}$$

We can express the contribution of given drafting system to the total square mass irregularity of output product by so called machine irregularity ($CV_{machine}$):

$$CV_{machine}^2 = (CV_2^2 - CV_{lim2}^2) - (CV_0^2 - CV_{lim0}^2) \tag{5}$$

Using equation (4), we can also express the resulting total square mass irregularity of linear fibrous product on the output from the drafting device CV_2 as:

$$CV_2^2 = CV_{lim0}^2 . P_c + CV_{S0}^2 + CV_P^2 + CV_{VS}^2 \tag{6}$$

where P_c is total draft, CV_p is additional square mass irregularity of fibrous product inducted in the drafting device and CV_{VS} is systematic square mass irregularity of fibrous product developed from latent irregularity by total draft in the drafting arrangements.

Substituting formulas (3) and (6) into the equation (5) we obtain:

$$CV_{machine}^2 = CV_P^2 + CV_{VS}^2 \tag{7}$$

From formula (7) it is evident that not only the additional irregularity but also the systematic square mass irregularity developed from the latent irregularity of input product influences the level of irregularity which the spinning system inserts into the final product.

Because the draft ratio in the infeed drafting zone is constant for given fibrous material, we will follow up relations in intermediate and main drafting zones of the given drafting device. For the intermediate drafting zone we can write:

$$CV_{PS}^2 = CV_{lim1}^2 . P1 + CV_{S1}^2 + CV_{P1}^2 + CV_{VS1}^2 \tag{8}$$

where CV_{PS} is total square mass irregularity of fibrous product after passing through the intermediate drafting zone; $P1$ means draft ratio in the intermediate drafting zone (intermediate draft ratio); CV_{lim1} is limiting square mass irregularity of fibrous product before entering into the intermediate drafting zone; CV_{S1} is systematic square mass irregularity of fibrous product before the intermediate drafting zone caused by both previous processes and infeed drafting zone; CV_{P1} is additional square mass irregularity caused by the intermediate drafting zone and CV_{VS1} is systematic square mass irregularity of fibrous product developed from the latent mass irregularity in the intermediate drafting zone.

For the main drafting zone we can write:

$$CV_{PH}^2 = CV_{lim2}^2 + CV_{S2}^2 + CV_{P2}^2 + CV_{VS2}^2 \tag{9}$$

where CV_{PH} is total square mass irregularity of fibrous product after passing through the main drafting zone, CV_{lim2} is limiting square mass irregularity of fibrous product after passing through the main drafting zone; CV_{S2} is systematic square mass irregularity of fibrous product before the main drafting zone caused by previous drafting processes; CV_{P2} means additional square mass irregularity of fibrous product induced in the main drafting zone and finally CV_{VS2} is systematic square mass irregularity of fibrous product developed from the latent irregularity in the main drafting zone.

Because of below mentioned formulas (10a) and (10b) hold:

$$CV_{lim2}^2 = CV_{lim1}^2 . P1 . P2 \tag{10a}$$

$$CV_{S2}^2 = CV_{S1}^2 + CV_{P1}^2 + CV_{VS1}^2 \tag{10b}$$

we can write:

$$\begin{aligned} CV_{PH}^2 = CV_{lim1}^2 . P1 . P2 + (CV_{S1}^2 + CV_{P1}^2 + CV_{VS1}^2) \\ + CV_{P2}^2 + CV_{VS2}^2 \end{aligned} \tag{11}$$

where $P2$ means main draft ratio.

From formulas (10b) and (11) it is obvious that with increasing draft ratio $P1$ in the intermediate drafting zone the component CV_{S2}^2 will have a significant effect on yarn mass irregularity. The component will increase irregularity of final yarn even if the main draft ratio will be reduced.

3 EXPERIMENT

Within the experiment, mass irregularity of 100% Tencel air-jet spun yarns as well as number of yarn faults were analyzed in dependence on the intermediate draft ratio as well as the main draft ratio.

3.1 Materials and methods

Tencel staple fibers (38 mm, 1.3 dtex) were used for production of air-jet spun yarns of nominal count 23 tex. Samples of yarns were spun on the Rieter Air-jet spinning machine J20 from a sliver which was processed in 3 passages of doubling and drawing after carding. Three different levels of sliver linear densities (see Table 1) were used for the experiment to analyze influence of main draft ratio on the yarn mass irregularity and yarn faults. Within each level of sliver linear densities, three levels of intermediated draft ratio were set to observe the influence of intermediate draft ratio on the yarn mass irregularity. The infeed draft and other spinning parameters were kept constant and they were set in accordance with the processed raw material and yarn count.

Table 1 Proposal of experiment

Trial Nr.	V1	V2	V3	V4	V5	V6	V7	V8	V9
Sliver linear density [ktex]	3.65	3.65	3.65	4.09	4.09	4.09	4.61	4.61	4.61
Infeed draft *P0*	1.78	1.78	1.78	1.78	1.78	1.78	1.78	1.78	1.78
Intermediate draft *P1*	1.97	2.30	2.64	1.97	2.30	2.64	1.97	2.30	2.64
Main draft *P2*	45.79	38.95	33.93	50.2	43.13	37.39	56.52	48.55	42.41
Total draft	160.6	159.46	159.45	176.06	176.6	175.69	198.19	198.79	199.3
Real average yarn count [tex]	22.72	22.89	22.89	23.23	23.16	23.28	23.26	23.19	23.13
Nozzle air pressure [MPa]	0.6								
Spinning nozzle	Z-1								
Spinning tip type	U1.2mm/A0.8								
Delivery speed [m.min^{-1}]	400								

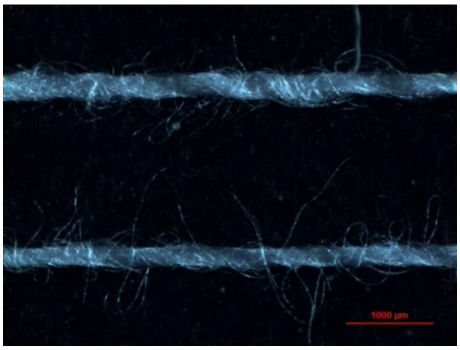

Figure 2a Longitudinal view on yarn samples (Trial Nr.8)

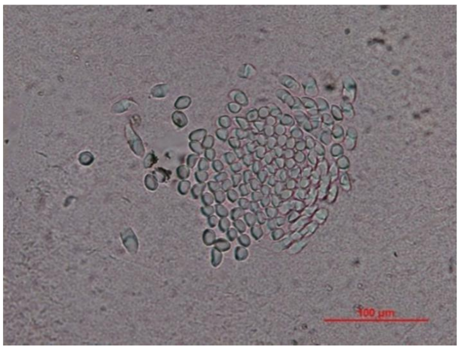

Figure 2b Cross-sectional view on yarn samples (Trial Nr.8)

For each trial, 5 bobbins were spun. For illustration of fasciated yarn structure, the longitudinal view on the yarn sample and yarn cross-section was made (see Figure 2a and 2b). The Uster Tester IV-SX was used for measuring yarns as well as slivers mass irregularity. Slivers were measured for 5 min with the speed of 25 m/min, whereas yarns were measured for 2.5 min with the speed of 400 m/min. For each yarn sample, 15 measurements were done.

To investigate the effect of main draft ratio on yarn mass irregularity (when the intermediate draft ratio is kept constant), it is necessary to analyze sliver mass irregularity and take it into account. The negative effect of measured sliver mass irregularity can be eliminated by calculating and comparing machine irregularity. Except for draft, all machine process parameters were constant for all tested yarn samples. Based on this, we can assume that square mass irregularity of yarn is the same as square mass irregularity of linear fibrous product in the output from drafting arrangements and thus we can calculate the machine irregularity using formula (5). The limiting mass irregularity is defined by the formula:

$$CV_{lim} = \frac{100}{\sqrt{n}} \tag{12}$$

where n is mean number of fibers in yarn (sliver) cross-section calculated as ratio of mean yarn (sliver) count and mean fiber fineness.

4 RESULTS AND DISCUSSION

4.1 Square mass irregularity

Table 2 shows results of square mass irregularity of sliver on various length sections. From the table, it can be seen that mean value of mass irregularity of sliver in the cross-section (CV_{sliver}) decreases with increasing linear density of slivers. This phenomenon is known. Finer sliver has a lower number of fibers in the cross-section and it expresses in growing of mass variability. Sliver mass irregularity on longer cut length has fluctuating tendency and it is caused by previous technological stages.

Table 2 Results of sliver mass irregularity

Sliver fineness [ktex]	CV_{sliver} [%]	CV_{sliver} (1m) [%]	CV_{sliver} (3m) [%]	CV_{sliver} (5m) [%]
3.65	6.96	1.01	0.63	0.5
4.09	6.28	1.15	0.72	0.6
4.61	5.82	0.96	0.67	0.5

Figure 3a demonstrates spectrogram of sliver. Significant higher harmonic components of mass irregularity at the wavelengths λ=50 cm and λ=1 m are probably caused by previous technological levels. Figure 3b shows the example of spectrogram of yarn mass irregularity. It can be seen that yarn has not any significant periodical irregularity. Spectrograms of slivers as well as yarns also show that higher periodical irregularity of sliver on long wavelengths does not fully transform into the yarn due to draft on the wavelength corresponding to the value equal to λ^*P_c. The reason can be attributed to the relatively short length of measured yarn for this analysis and less statistical reliability of spectrogram results on the long wavelengths.

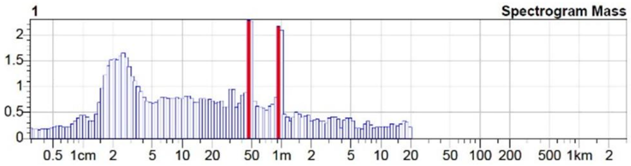

Figure 3a Spectrogram of sliver mass irregularity (Sliver fineness 4.09 ktex)

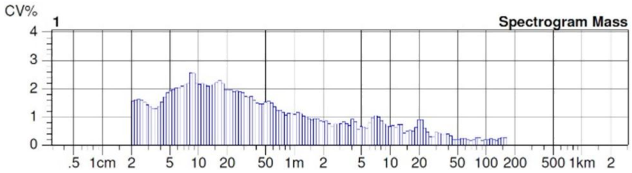

Figure 3b Spectrogram of yarn mass irregularity (Trial No. V8)

Figure 4 shows dependence of yarn square mass irregularity (CV_{yarn}) on the main draft ratio. Contrary to known theory, it can be seen that when keeping the intermediate draft ratio constant, the yarn mass irregularity decreases with growing the main draft ratio. The yarn mass irregularity also deteriorates with growing the intermediate draft ratio (or we can say with decreasing main draft ratio) when sliver mass density is kept constant. These results confirmed the theory mentioned above. When increasing the intermediate draft ratio, the component CV_{S2}^2 influences total yarn mass irregularity negatively. At increasing intermediate draft ratio $P1$, this component is affected by increase in components CV_{P1}^2 and CV_{VS1}^2. It is due to the character of the intermediate drafting zone and resulting friction force field in the longitudinal direction which corresponds to the drafting zone with missing a guiding (controlling) device. Due to its arrangements, the main drafting zone allows to minimalize the increase in additional mass unevenness.

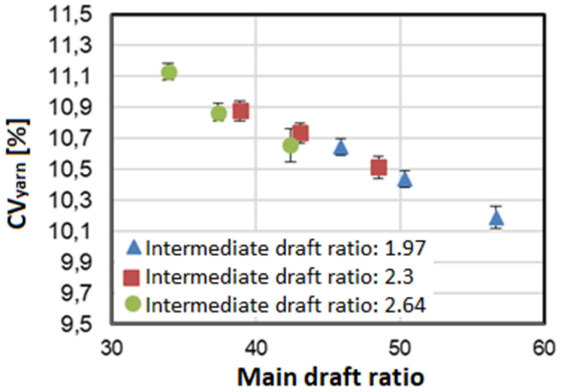

Figure 4 Dependence of yarn mass irregularity on main draft ratio and various intermediate draft ratios

Two-way variance analysis Anova confirmed a statistically significant effect of both intermediate draft ratio and sliver linear density on the yarn mass irregularity at the significance level of 5%. However, the significance of mutual interaction of these two factors was not statistically confirmed (see the results in Table 3).

4.2 Machine irregularity

Figure 5 presents machine irregularity in dependence on the main draft ratio for various intermediate draft ratio.

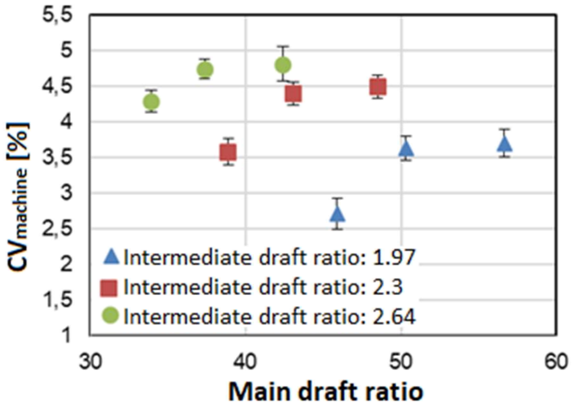

Figure 5 Dependence of machine irregularity on main draft ratio and various intermediate draft ratios

Table 3 Results of two-way Anova

Property	Source of variance	F-ratio	Critical quantile	Results	p-value
CV_{yarn} (CV_m)	Intermediate draft ratio	172.68	3.07	Significant	$3.55.10^{-36}$
	Sliver linear density	146.93	3.07	Significant	$4.22.10^{-33}$
	Interaction	1.30	2.45	Non-significant	0.27
Thin places (-40%)	Intermediate draft ratio	27.28	3.07	Significant	$1.61.10^{-10}$
	Sliver linear density	42.42	3.07	Significant	$1.03.10^{-14}$
	Interaction	2.62	2.46	Significant	0.04
Thick places (+50%)	Intermediate draft ratio	8.50	3.07	Significant	$3.48.10^{-4}$
	Sliver linear density	0.77	3.07	Non-significant	0.46
	Interaction	0.61	2.46	Non-significant	0.66
Neps (+200%)	Intermediate draft ratio	2.49	3.07	Non-significant	0.09
	Sliver linear density	1.25	3.07	Non-significant	0.29
	Interaction	0.95	2.46	Non-significant	0.43

The results showed that:

- When keeping the intermediate draft ratio constant, the main draft ratio is a significant factor which increases machine irregularity. This result is in accordance with theory presented above. Based on the theoretical analysis mentioned above, we can also say that systematic square mass irregularity developed from the latent irregularity by the draft probably contributes to the increase in machine irregularity. Based on this, we can conclude that when the intermediate draft is constant, decreasing values of measured yarn square mass irregularity (CV_{yarn}) with growing main draft ratio (due to higher sliver linear density) was caused by mass irregularity of input sliver which corresponds to the irregularity components CV_{lim0} and CV_{s0}. Finer sliver has higher measured valued of mass irregularity compared with course sliver. This irregularity transforms into the yarn and thus influences total square mass irregularity of yarn more than the drafting device itself.
- When sliver linear density is constant, the value of machine irregularity increases with increasing level of intermediate draft ratio (and thus with decreasing main draft). This result is in agreement with the previous one and verifies the higher importance of intermediate draft ratio on total yarn mass irregularity compared with the main draft ratio.

4.3 Yarn faults

Average values and corresponding 95% confidence intervals of yarn faults (thin places (-40%), thick places (+50%) and neps (+200%)) are presented in Figure 6a-6c. Number of thin places (-40%) was observed instead of thin places (-50%) because of zero number of faults in this category. Selected results of two-way analysis of variance are mentioned in Table 3. Results of numbers of thin places have the same trend as results of total mass irregularity of yarns. Number of thin places decreases with decreasing intermediate draft ratio and with increasing linear density of supplied sliver. Results of two-way Anova show that sliver linear density, the intermediate draft ratio as well as interaction of these two factors have a statistically significant effect on number of thin places (-40%). The linear density (and thus the main draft ratio at constant level of intermediate draft ratio) is a factor with a higher significant effect. However, it is clear from the graph in Figure 6a that, in the terms of overlapping confidence intervals, the statistically significant difference is only between the numbers of thin places of yarn sample spun from sliver of linear density 3.65 ktex at intermediate draft ratio of 2.64 and yarn sample made from a sliver of 4.61 ktex at intermediate draft ratio of 1.97. Number of thick places (+50%) shows similar results as in case of thin places, but in this case the effect of interaction of sliver linear density and level of intermediate draft ratio is a statistically insignificant. The results can be attributed to both mass variability of supply sliver, which is higher in the case of finer sliver, and negative effect of the intermediate drafting zone which is stronger with growing intermediate draft ratio. Based on results of two-way Anova, we can state that in the case of number of yarn neps (+200%) the effect of observed factors is statistically insignificant in significance level of 5%. However, we have to note that thanks to the specific yarn structure, the Uster Tester can also records as a nep the place where the ends of the wrapping fibers are not tightly twisted around the yarn core due to the air flow in the nozzle.

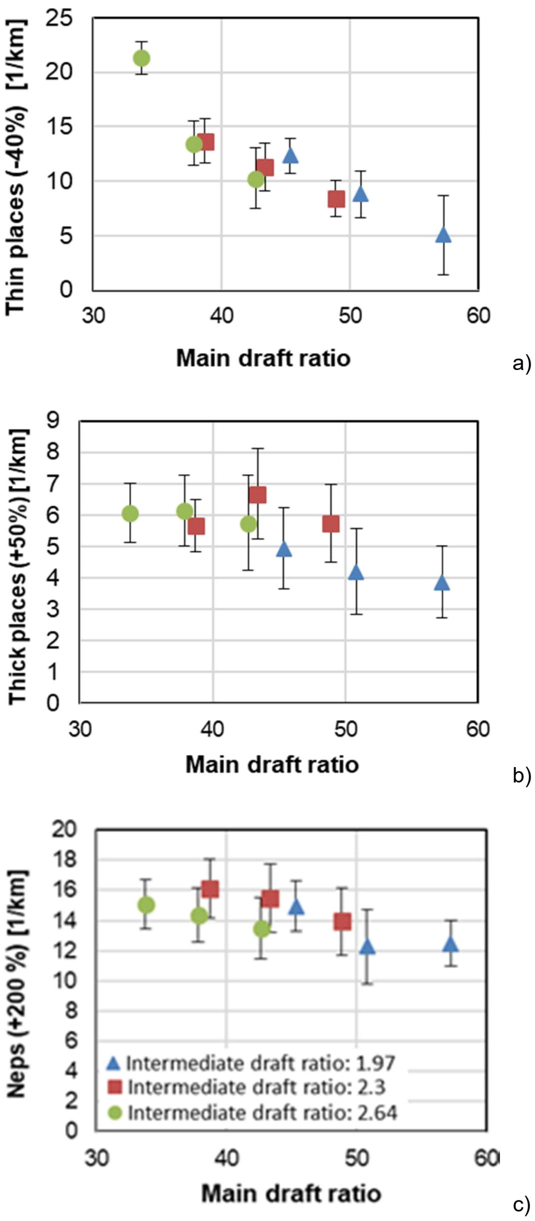

Figure 6 Dependence of yarn faults on main draft ratio and various intermediate draft ratios

5 CONCLUSIONS

In this work, the analysis of draft in the four-roller two-apron drafting device of air jet spinning machine was done together with theoretical analysis of transformation of mass irregularity of fibrous product by this drafting unit. The effect of intermediate and main drafting zones was observed. Within the experiment, mass irregularity of air-jet yarns of the same count, produced with various setting of intermediate and main draft ratio, was evaluated together with sliver mass irregularity and yarn faults. Based on theory, the mass irregularity of fibrous product is deepened by the draft mostly. Despite the fact that the main draft ratio is much higher compared with the intermediated draft ratio, this study shows that the intermediate draft ratio has more significant influence on the yarn mass irregularity than the main draft. It can be explained by the fact that fibers move in the intermediate drafting zone without aprons. The aprons are a part of the main drafting zone, and they control the fibers movement in the zone. Thus, in this zone, they minimalize the creation of the additional irregularity, which is one of a component of total yarn mass irregularity. The additional irregularity is probably highly deepened in the intermediate drafting zone due to the fact that various drafting force is applied on each fiber in the zone and change of speed of fiber movement does not occur at the same place. Also the irregularity of supplied sliver (limiting and so called systematic) has negative influence on the total yarn mass irregularity. The experiment shows that for achieving the lowest value of total mass irregularity of tested yarn samples it is suitable to use the lowest value of intermediate draft ratio ($P1$ = 1.94) in combination with coarser supply sliver (4.61 ktex). Compared with finer sliver, the sliver with higher linear density (from the observed range) seems to be suitable because it has lower irregularity thanks to higher number of fibers in the sliver cross-section and due to lower draft ratios used in previous spinning processes. When observing number of yarn faults, the same trends were achieved. But the statistically significant differences were recorded only in the case of thin places (-40%). Finally, based on Uster Statistics, we have to note that tested samples of air jet yarns have lower irregularity. Also the differences between minimum and maximum CVm values were in the range up to 5%. For verification of results it is necessary to extend the experiment in terms of both wider draft range and raw material and to observe impact of yarn mass irregularity on various yarn properties.

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