Preferred citation: F. Lundell, D. Söderberg, S. Storey and R. Holm. The effect of fibres on laminar-turbulent transition and scales in turbulent decay. In **Advances in Paper Science and Technology**, *Trans. of the XIIIth Fund. Res. Symp. Cambridge, 2005*, (S.J. I'Anson, ed.), pp 19–34, FRC, Manchester, 2018. DOI: 10.15376/frc.2005.1.19.

THE EFFECT OF FIBRES ON LAMINAR-TURBULENT TRANSITION AND SCALES IN TURBULENT DECAY

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ABSTRACT

Two physical phenomena which determine fundamental possibilities of paper forming are studied. The two phenomena are (*i*) laminar/turbulent transition and (*ii*) decay of turbulence. At first, the relevance of the processes to paper making is reviewed and discussed. The state of the boundary layers (laminar or turbulent) on split vanes and the decay of turbulence in the free stream are found to be of uttermost importance for the control of layer purity, formation and other properties of the final paper. Experiments in which these two processes are studied by visualisations are presented. The experiments emphasize the impact of fibres on these processes, as compared to what is found with pure water. All experiments are performed in model experiments were the structures in the flow are visualised by the addition of small, flake-like particles. It is shown that the addition of fibres radically change the physics of the flow. In a water table experiment, the addition of fibres is seen to promote the production of turbulent spots. At high enough fibre concentrations, the flow of water and fibres is fully turbulent even if a flow of pure water is laminar. In decay of turbulence, the fibres are seen to radically change the energy transfer between different scales so that intermediate and small scales remain active for longer times. It is concluded that fibres have large effects on laminar-turbulent transition and turbulence decay and that improved knowledge of these effects are a corner stone in the understanding of head box flow and its relations to the resulting paper quality.

1 INTRODUCTION

1.1 Turbulence in pulp and paper research

Within the area of pulp and paper research the concept of turbulence is well known and there are many investigations related to the subject. Most of these have focused on the flocculation of fibre suspensions [4, 5, 6, 3]. The direct influence on paper properties has also been considered by Kiviranta & Dodson (1995) [7]. There are also several attempts to model the headbox flow, neglecting the presence of fibres, using CFD (Computational Fluid Dynamics) and turbulence models originally developed for newtonian fluids (water). However, Parsheh (2001) [9] showed that already the acceleration in the headbox can lead to major errors if using standard turbulence models [9]. The effect of fibres on the flow is of course one more possible error source for such models.

1.2 Effect of fibres on turbulence and transition

The pulp and paper research community has focused on the effect of turbulence on fibre flocculation, fibre orientation, formation etc. However, it is not only fibres which are affected by the turbulence, there is also an opposite effect the turbulence. Bennington & Mmbaga (2001) [2] that fibres changes the nature of dissipation of the turbulent energy. In a turbulent fibre suspension, the turbulent energy is not dissipated to heat at small scales, as it is in pure water. Instead, the dissipation occurs due to fibre interaction. Some of the issues and possible effects which arise when classical theories in fluid mechanics of newtonian fluids are applied to flows of fibre suspension were discussed by Norman & Söderberg (2001) [8].

One well known effect is that the friction drag decreases when fibres are added to the flow. This effect has resulted in a large number of fundamental studies. Paschkewitz *et al* (2004) [10] performed a direct numerical simulations of turbulent flow with fibres in a channel were performed. It was proposed that the fibres inhibit the so called bursts, which create a large portion of the turbulent energy close to a wall, and thereby reduces the drag.

1.3 Turbulence and transition in papermaking

Apparently, It is not only the fibres which are affected by turbulence in the flow; there is also an effect in the other direction. Since the turbulence in the head box and on or in between the wire/s is known to affect the paper quality, a better understanding of this effect would be beneficial for modelling and improvements of the forming process.

It could be believed that transition, the process during which a laminar flow turns into a turbulent one, is of limited interest for papermaking since the Reynolds number (the nondimensional number which is used to determine whether a flow is prone to be turbulent or not) usually are very high in a head box, indicating turbulent flow. However, Talamelli *et al* (2002) [11] showed that the acceleration in the head box can force the velocity boundary layers which form on e.g. the vanes in a multilayered headbox to re-laminarize.

The state of the boundary layers on the vanes, laminar or turbulent, determines the behaviour of the wake after the vane. In order to understand the mechanisms controlling the mixing of layers in multilayered headboxes, it is therefore of uttermost importance to understand the effect of fibres on flow instabilities. However, the stability characteristics of fibre suspensions can be quite different from those of a newtonian fluid (such as pure water). Theoretical studies of the stability of fibre suspensions are hard to do and it is always necessary to apply some simplifications. It has however been done quite a few times over the years. Asaiez (2000) [1] concludes that the fibres have a stabilizing effect on free shear flows. As stated in the introduction of that paper, some of the previous theoretical studies have come to the conclusion that fibres are destabilizing the flow and the result seems to be sensitive to how the effect of fibres are modelled.

1.4 Present study

In the present study, we aim at demonstrating the effect of fibres on turbulence decay and transition. From previous studies it is clear that turbulence decay and laminar/turbulent transition (or re-laminarization) of fibre suspensions are key factors which have to be mastered in order to understand, model and control the flow in the head box. This study is entirely based on visualisation images and in section 2 we describe the visualisation method and the setups. The results are presented in section 3. The results are discussed and conclusions are made in the light of papermaking in section 4.

2 METHODS AND EQUIPMENT

The experiments were performed in three different setups which will be described below. The fluid phase was pure water in all experiments. Three different fibre-phases were used. The first is well-defined Cellulose Acetate Fibres (CAF) with a diameter 50 μm and a density of 1300 kg/m^3. Two lengths, 0.5 and 2 mm, of CAF were used. The second kind of fibre is 2.7 mm long nylon fibres, which were used for some tests. The third kind of fibres which has been used was softwood kraft pulp. The flow of these suspensions was visualised and filmed by digital cameras.

Throughout the paper, x is used for the streamwise coordinate and y for the cross-stream coordinate.

2.1 Visualisations

The structures in the flow were visualised by adding Iriodin tracer particles. Iriodin are reflective platelets with a size of ≈ 5 μm. Thanks to their geometry, the mean orientation of the particles depend on the local shear gradient: occasionaly, the platelets flips in the shear just like fibres, but the observed light patterns are integrated over many particles. If the particles are illuminated from the side, they reflect the light. The local light intensity seen by an observer thus depends on the mean orientation of the particles at that position. Even if the particles are evenly distributed in the flow, the intensity of the reflected light varies if the shear gradients vary. These particles are an excellent tool for the study of flow structures in transition or turbulence and has been used extensively for this purpose in studies of pure water.

2.2 Set-up for the study of laminar-turbulent transition

The effect of fibres on transition was investigated using water table flow, which is a well defined generic flow case. The setup is sketched in Figure 1. A fibre suspension was pumped to an upper holding tank by a membrane pump. The suspension then flowed down the inclined plane and the velocity was controlled by the tilt angle and pump rate. The flow was visualised from above and the appearance of turbulence and turbulent spots are clearly visible in the visualisations. The experiments were performed with different concentrations of 0.5 mm long CAF and Nylon fibres.

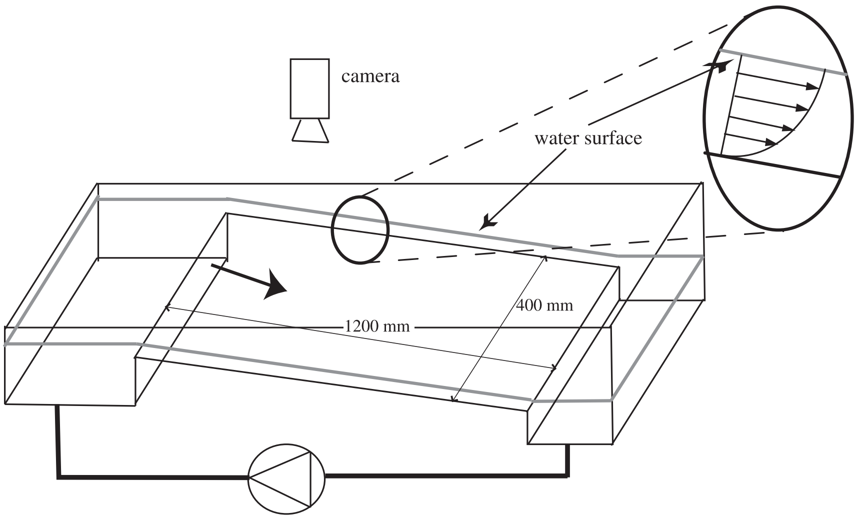

Figure 1 Sketch of the watertable used to study the effect on fibres on laminar/turbulent transition.

2.3 Set-ups for the study of turbulent decay

For the case of turbulent decay, two set-ups were used. The first was a plain transparent container. An electromagnetic stirrer forced the liquid in the containers into turbulent motion. After the stirrer was turned of the structures in the decaying turbulent flow was recorded though one of the sides of the container. The turbulent structures are clearly visible in the visualisations and spectral analysis of the images gives quantitative data on the decay of turbulence. These experiments were performed with the softwood kraft pulp.

The second set-up is sketched in Figure 2. The liquid is pumped through a square duct, through a turbulence generating block (which is seen as the gray plug with holes in the duct). The camera monitors the turbulence generated by the block as it is convected downstream with the flow. Image sequences of the flow were taken and the images analyzed. The experiments in the duct were performed with 0.5 and 2 mm long CAF fibres.

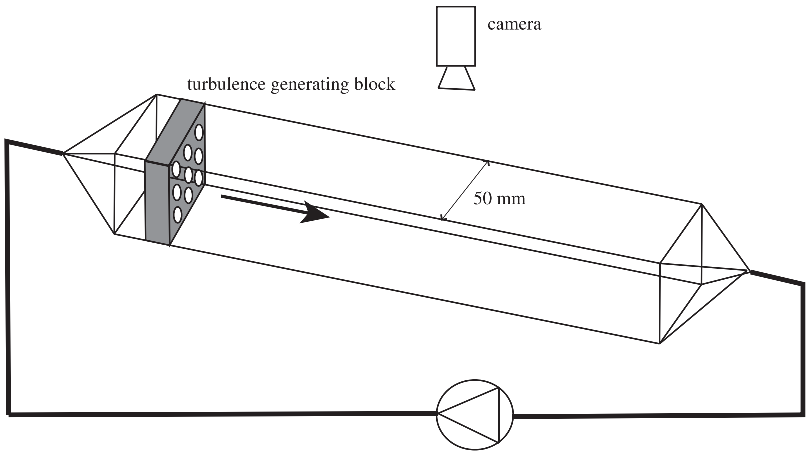

Figure 2 Sketch of the duct used to study the effect on fibres turbulent decay.

3 RESULTS

3.1 Laminar-turbulent transition

Before examining the effect of fibres on transition, the flow was carefully set at the critical speed and liquid layer thickness. Carefully trimmed, the flow was turbulent in the beginning and re-laminarized while flowing down the water table. This was achieved by tilting the plane steeply to obtain turbulent flow and then adjusting the tilt angle and flow speed until re-laminarization was observed. With no fibres present, the turbulence was observed to propagate approximately 0.20 m along the inclined plate before the flow was re-laminarized. Fibres were then introduced into the flow, and the concentration slowly increased. The fibre concentration ranged from $N = 0.005$ to $N = 4$, where N represents the crowding number defined as nl^3 where n is the number density and l the length of the fibres. Without fibres, the flow was observed to be generally laminar, with occasional turbulent spots, see Figure 3 (a). When the 2.7 mm Nylon fibres were added, no change in the flow was observed for any concentration. However, adding small amounts of CAF produced striking changes. Figure 3 shows a significant increase in turbulence with increasing crowding number. The spots were observed to grow in size and become more numerous. In addition, each spot persisted for a longer period. For concentrations above $N = 0.2$, the turbulence is seen to cover most of the inclined plane. The spots became connected to each other and produced oblique waves of turbulence.

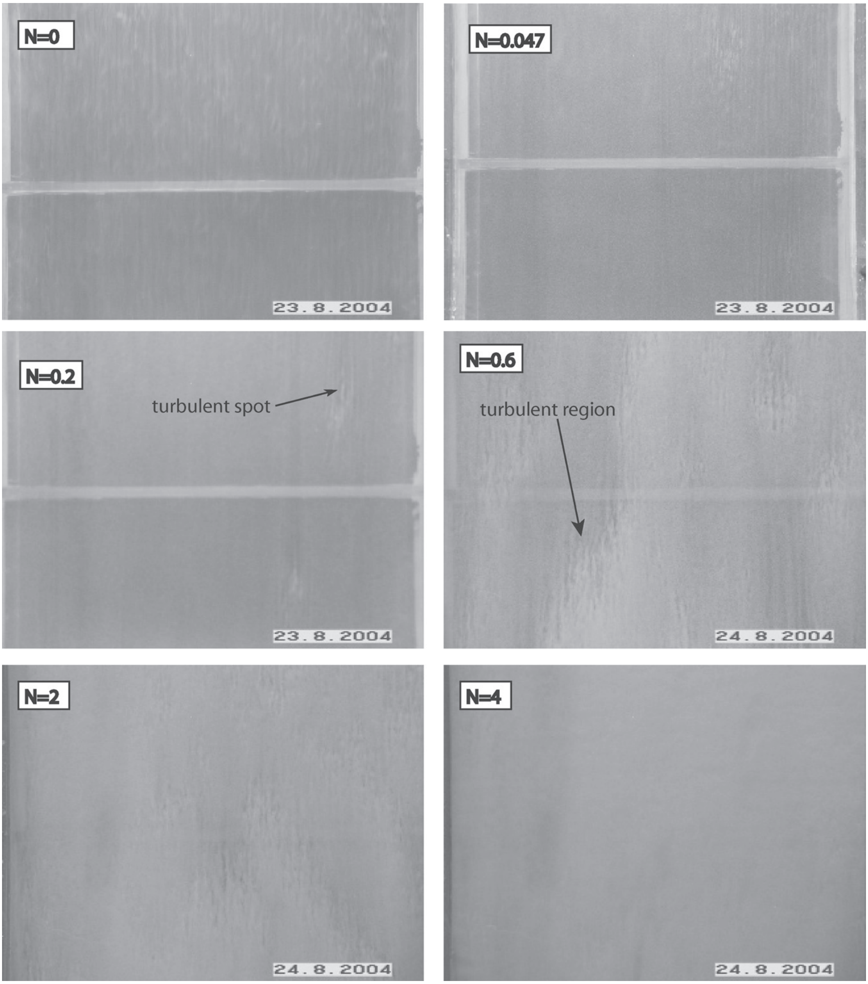

Figure 3 Visualisations of the flow down the watertable with increasing fibre concentration as indicated in the labels. The flow direction is downwards.

3.2 Turbulent decay

3.2.1 Decaying turbulence in the container

Example images from the visualisations of decaying turbulence in the containers are shown in Figure 4. The top row shows the container with pure

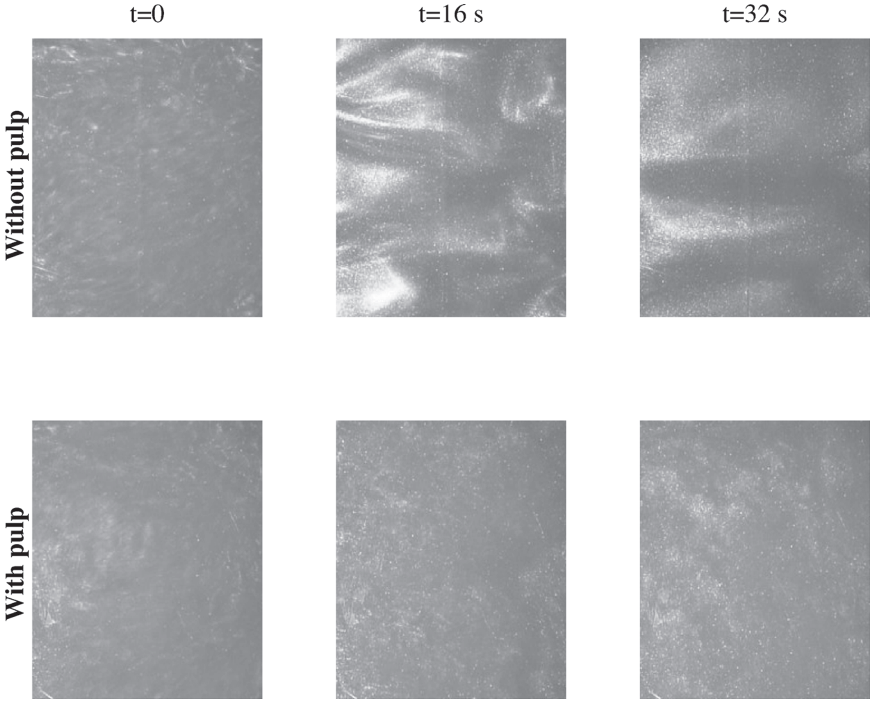

Figure 4 Images of the turbulent structures in a container initially stirred by a laboratory stirrer. Top row: without pulp, bottom row: with pulp. The stirrer is turned off at $t = 0$.

water at three time instants, $t = 0$ s, 16 s and 32 s, where the first time is directly after the stirrer has been turned off. The bottom row represents the same times but with pulp fibres added at a concentration of 1.5 g/1 (0.15%). At $t = 0$ there is a lot of small scale motion for both cases but for the case without fibres, the small scales dies out quickly and only large scales prevail after 32 s. With fibres, a completely different development is seen. In this case, the small scales seem to remain and continue to be present also at 32 s. When the videos are observed, additional features can be seen. The case without fibres seems to be governed by a shift from small scales to larger as the turbulence dies out, while the case with fibres seems to be governed by a decay at an intermediate length scale.

For a newtonian fluid, the process of turbulence decay is described in standard textbooks (e.g. Tennekes & Lumley (1972) [12]). In intensive turbulence, the turbulent energy is dissipated to heat by viscosity at small scales. The turbulence energy is transported from large scales to the small scales thanks to the non-linear dynamics of the turbulence. As the total energy of the turbulence decreases due to dissipation, the scale at which the dissipation takes place grows (an alternative explanation is that as the turbulent energy decreases, the turbulence does not manage to push the turbulent fluctuations to very small scales any more; the viscous forces becomes stronger than the momentum forces at a larger scale). This means that the scales which are observed in the flow goes from a wideband distribution to large scales, which remain for long times. It should be emphasized that the non-linear dynamics demands a continuous scale distribution: all scales must be active everywhere for the turbulent energy to be transported as described above. This is the process seen in the top row of Figure 4. Looking at the bottom row, it is obvious that the pulp radically changes or inhibits this process.

In order to quantify the data from the visualisations, spectral analysis of the images was performed. The spectral analysis provides data on the distribution at different scales in one image and the development of the amplitudes from one image to the other. Figure 5 shows such spectra for the two cases. The spectra have been calculated by performing the PSD (Power Spectral Density estimate) of each horizontal line and vertical column of similar images as those presented in Figure 4. The spectra from five consecutive images (0.66 s total time) have then been averaged in order to get well converged spectra. The figure presents the spectra as a function of the wavenumber k. In Figure 5 (a), it is seen that without pulp the small-scale (high k) peak decreases while there is a wide band of larger scales whose relative importance increases with time. This is a very different scenario compared to the case with pulp, Figure 5 (b), where the small-scale peak (high k) is dominant throughout the process.

3.2.2 Convected turbulence in the duct

In the duct, the turbulence develops as it is convected downstream. The process is similar to what occurs in the container after the stirrer has been turned off: further downstream, the turbulence is older and a newtonian fluid is expected to display larger scales, as compared to closer to the turbulence generator. This process is seen in the top image of Figure 6, which shows the turbulence in the duct with pure water. The mean flow velocity is 49 mm/s and flow is from left to right. The left part of the image is right after the turbulence generator. To the left, the flow is dominated by small scales whereas larger scales prevail to the right, where the turbulence is older. The data from

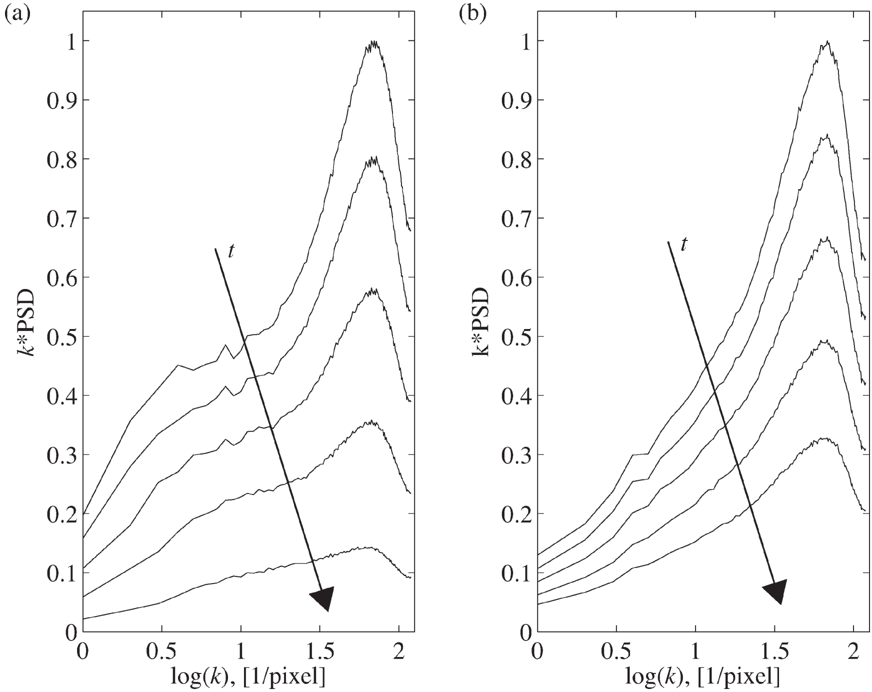

Figure 5 Spectra quantifying the scales seen in Figure 4; (a) without pulp and (b) with pulp.

the duct which is to be presented consists of image sequences of the flow with and without CAF with $l = 0.5$ and 2 mm at crowding numbers ranging from 0 to 10.

In order to get a clear visuallization of the turbulent structures in the flow, the images were treated as shown in Figure 6. First, the average of all images in each sequence was calculated (second image from the top). By subtracting the average of the sequence from each image, the time unique features of each image is extracted. The turbulent structures which give the visualisation flakes an orientation which maximizes the reflected light are then seen as white regions against a black background (third image from the top). Finally, the image is inverted, so that the turbulent structures are black whereas the background is white (bottom image).

The results on decaying turbulence in the container indicate that as fibres are added to the flow, the turbulent structures should remain small

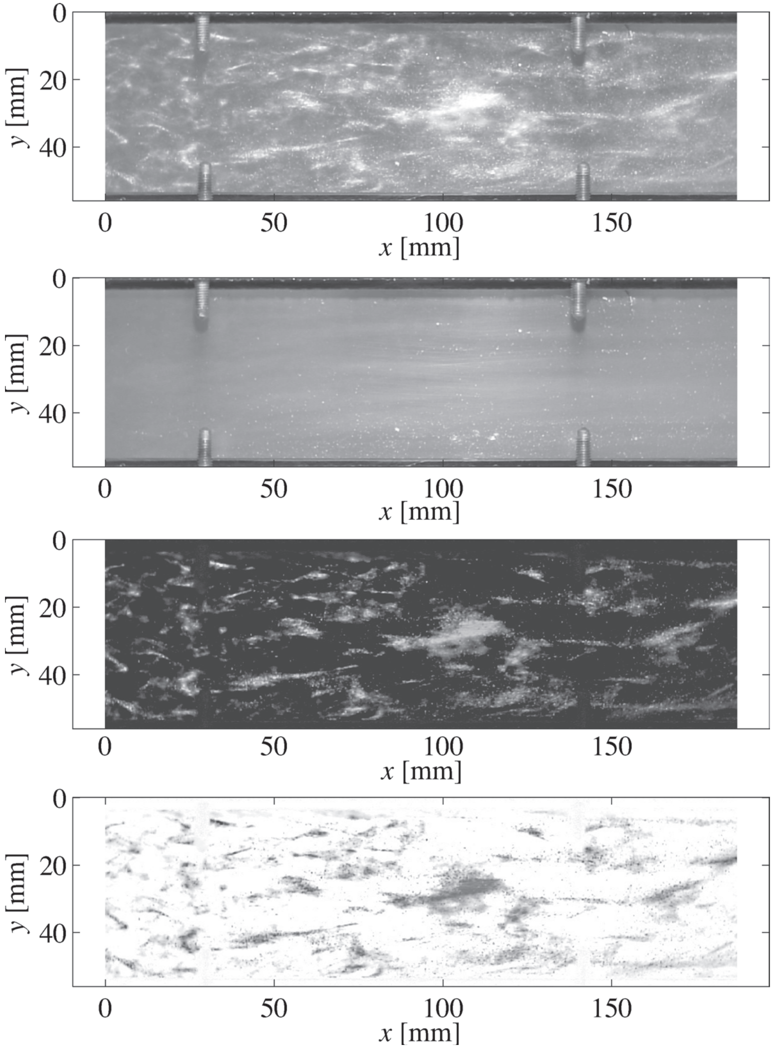

Figure 6 Top: image of the flow in the duct without fibres, flow is from left to right. From top to bottom, the image treatment process is demonstrated: starting from the original images (top), the average of all images in the sequence is calculated (second). The average is subtracted from each image so that only the time dependent structures are seen (third). Finally, the images are inverted so that the turbulent structures are black against a white background (bottom).

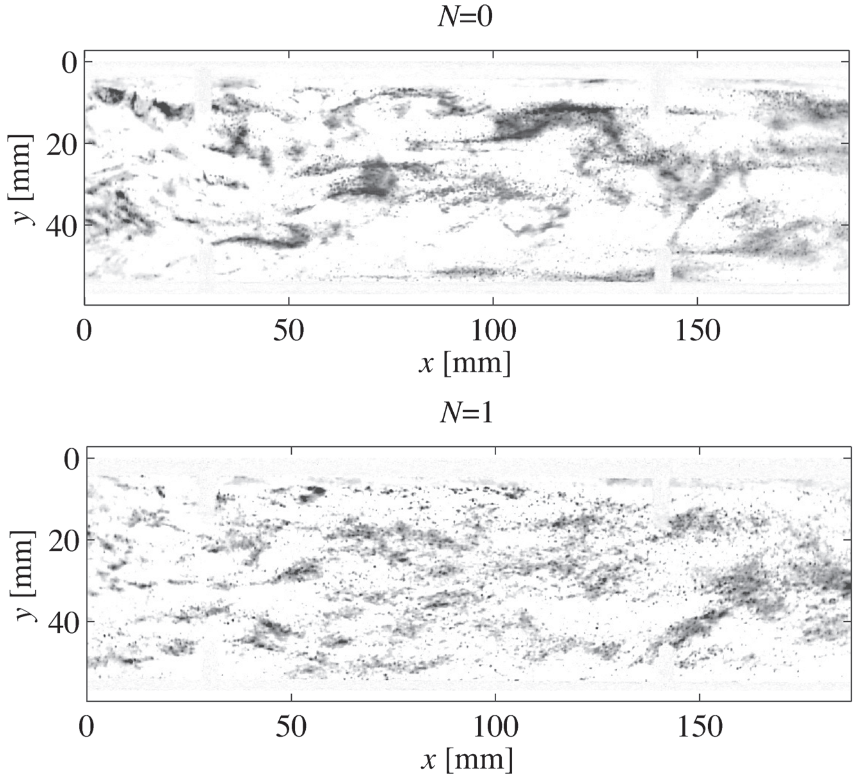

Figure 7 Example of treated images of the flow in the duct. Top: pure water, bottom: CAF, $l = 0.5$ mm, $N = 1$.

throughout the region under study. As expected, this effect is seen in Figure 7. In (a), where pure water is used, the development towards larger scales is clearly seen while in (b), were CAF fibres with $l = 0.5$ mm are added to the water at a concentration of $N = 1$, the small scale structures are seen to prevail throughout the test section. In the following, the scale of the turbulent structures will be extracted from the images and the scale development compared for different fibre concentrations and fibre lengths.

In Figure 8, the process by which the dominant scale of the turbulence is extracted from the images is explained. Figure 8 (a) shows an example of a vertical profile of pixel values from one x position of the top image in Figure 7. From each profile, the minimum is determined. The minimum is marked with a circle in Figure 8 (a). The width of this structure is then determined as

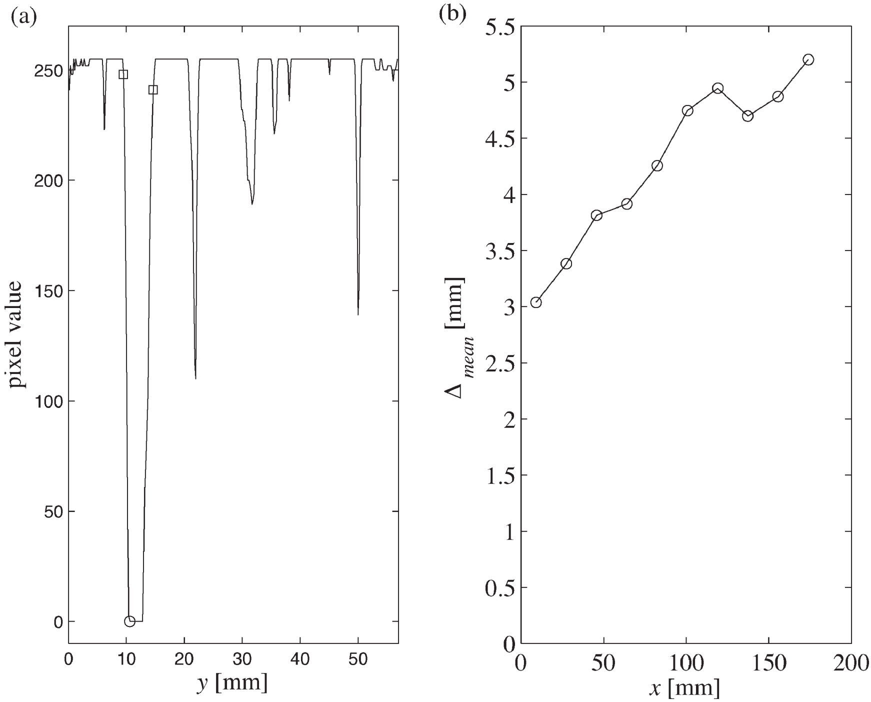

Figure 8 Explanation of the quantification of the image data. (a): From the pixel values of each column, the length of the strongest structure in each column is detected (○: minimum value, □: endpoints of the structure). (b) Averaging this length over 100 columns and 60 images in the sequence, the development of the dominant scale as a function of the streamwise coordinate x is obtained.

the distance (counted by integer pixels) for which the pixel value stays above 10% of the amplitude of the peak (the amplitude of the peak is determined form the white background, which has a value of 255). The beginning and end of the peak marked with the circle are indicated with squares. Thus, a length is determined at each x position in every image of the sequence. This length is denoted $\Delta(t, x)$. Averaging the data from all images in a sequence, $\Delta_{mean}(x)$ is obtained. In Figure 8 (b), $\Delta_{mean}(x)$ is shown for the case of pure water. The dominant turbulent scale is seen to increase from 3 mm right after the turbulent generator to just above 5 mm close to the end of the region under study.

The dominant turbulent scales for fibre lengths l = 0.5 and 2 mm and crowding numbers N ranging from 0 to 3 (l = 0.5 mm) or 10 (l = 2 mm) are shown in Figure 9. For all cases, the dominant scale at x = 0 is constant and around 3 mm. This is explained by the fact that at this early stage, the turbulence is a function of the generator geometry only, the flow dynamics has not yet affected the scales. Further downstream, the fibres are seen to have a large effect on the development of the turbulent scales, especially the short fibres in Figure 9 (b). As the fibre concentration is increased, the development towards larger scales is inhibited and at the highest fibre concentration (N = 3), the dominant scale is actually decreasing as the flow propagates downstream. For the longer CAF fibres, the effect is smaller and not significant until N = 10 (Figure 9 (a)).

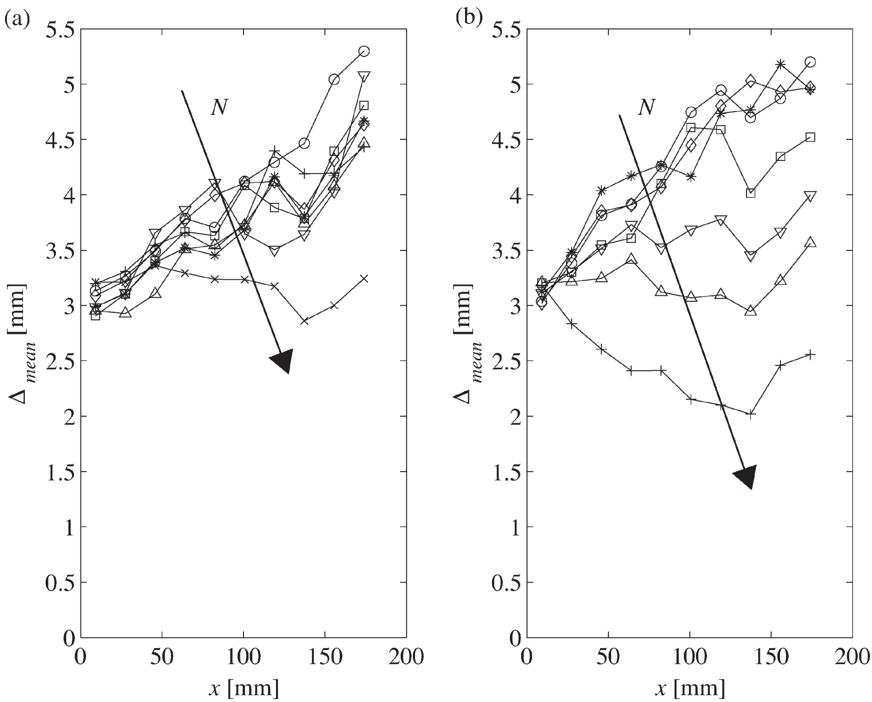

Figure 9 Streamwise development of Δ_{mean} as a function of x for l = 2 mm (a) and l = 0.5 mm (b). The markers are: ○: N = 0, ◇: N = 0.01, *: N = 0.03, □: N = 0.1, ▽: N = 0.3, Δ: N = 1, +: N = 3 and ×: N = 10.

4 DISCUSSION AND CONCLUSION

The effect of fibres on laminar-turbulent transition and scales in decaying turbulence has been studied. The addition of short Cellulose Acetate fibres caused definite changes in the flow and increased number of turbulent spots even though the Reynolds number decreases with increasing concentration as a result of the increase of the apparent viscosity. However, the longer Nylon fibres showed almost no effect on the flow. This could be due to the length scale of the fibres being very similar to the flow depth, which would confine the motion of the fibres to two dimensions, whereas shorter fibres can still rotate in three dimensions. Therefore, direct comparisons of the behaviour of the longer and shorter fibre species are inappropriate. In addition, the concentration of Cellulose Acetate fibres is clearly higher when compared to the concentration of Nylon fibre for the same crowding number.

A pulp concentration of 1.5 g/l (0.2%) is shown to drastically change the process of turbulence decay in a container. Without pulp, the movements on small scales decays first and the large scale remain. With pulp, the small scales remain active throughout the decay process. Similar effects were seen in the streamwise development of the dominant scale of turbulence being convected downstream in a square duct. Just like in laminar-turbulent transition, short fibres were seen have a larger effect than longer ones, at constant crowding number. A possible hypothesis is that the small scale does not represent turbulent fluctuations remaining from the beginning, but are a result of fibres or fibre bundles that create a shear in the direct surrounding of the fibre or bundle as it is rotated by the large scales. Such a mechanism could take energy from larger scales and deposit at scales which are on the order of the fibre or fibre bundle size.

The results show that fibres and pulp have major effects on two fundamental fluid dynamics processes: stability and turbulence decay. It is also observed that the magnitude of the effect depend on the nature (geometry, stiffness or other properties) of the fibres in question. It is well known that fibres have a strong impact but the presented results are new in two aspects. The first is that laminar-turbulent transition is more prone to occur when fibres are added, at least at lower concentrations. The second is a strong effect on the medium and small scales in the flow while the large-scale fluctuations are less influenced. For papermaking, these issues are of importance for several aspects in the forming process. In a headbox, the flows are considered turbulent and the boundary layers along the walls are possibly re-laminarizing. Thus, through an understanding of these phenomena the forming processes that have an influence on the sheet structure (anisotropy, formation etc.) can be mastered.

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Transcription of Discussion

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William Sampson University of Manchester

The crowding numbers that you quote seem to be very low for the fibre concentrations you are giving. The fibres you have used are of similar dimensions to say softwood fibres, although a little wider. At 0.5% consistency you report that you have crowding numbers only of about 2. Could you comment on this? Is this some other dimensionless version of the crowding number?

Fredrik Lundell

The crowding number used is just nl^3 where n is the number density of the fibres, l is fibre length and the fibres are 20 μm in diameter.

William Sampson

But, it is not necessarily per unit volume swept out by a single fibre. Perhaps there are some different volumes you are using and I am sure they are correct relative to each other?

Discussion

Øyvind Gregersen Norwegian University of Science and Technology

I was a bit surprised that you did not mention fibre networks or flocs in your presentation. My first interpretation when I saw the difference in flow structure when you increased the fibre concentration was that you were getting flocs. The flocs as quite large, coherent structures could be flowing downstream. Do you think that is the case?

Fredrik Lundell

I certainly think that is the case in a paper machine of course, but for these experiments, the cellulose acetate fibres are not as prone to floc as pulp fibres, because they are stiffer. Also, if you watch them sediment, they lie flat on the bottom rather than forming a network as pulp fibres do. Flocculation might become important for the short fibres but, for the longer 2 *mm* fibres, we have a continuous change of the scales in the turbulence with fibre concentration and flocculation is not an important driving mechanism, but rather the change due to the flow dynamics. This becomes obvious when you see the flows in reality and have a three-dimensional view.

Markku Kataja University of Jyvaskyla

First of all, I very much liked your results and it was nice to see your experimental data on phenomena which are very natural and easy to believe. Actually I think the next speaker will show some additional data, which are very well aligned with your results. I have just one question concerning the experimental method that you used in measuring the scales especially in the case of turbulence decay. If I understood it right, you put reflecting tracer particles in the fluid among the fibres and the scale information is obtained by analyzing the illumination pattern from single images. So, you do not actually observe the scales in the velocity pattern but in the illumination pattern?

Fredrik Lundell

That is a very good question, but, since the orientation of the particles depends on the velocity gradients, what we see are actually structures in the velocity. The difference between taking it in time or in space would simply depend on different aspects of the development of the vortical structures, but, in isotropic turbulence, it should be the same in all directions.

Markku Kataja

I can believe that that is true in the case where you have a clean fluid without fibres. My concern is that when you do have fibres, the effect of seeing smaller scales could come from the fact that you just do not see all the tracer particles. Fibres could be blocking some of the light and making the image more scattered in a way that is not necessarily related to actual velocity scales.

Fredrik Lundell

Again, at the highest concentration for the shorter fibre that might be the case, but that is an odd case compared to the others. We actually see the same type of scales all the time. The initial scale, the size right off the turbulence generating block is the same (3 *mm*) all through the experiments for pure water and for the highest fibre concentrations. For me it would be unfortunate if both fibre lengths had given the same size as the original flow. So the fact that we see the same scale, structure and size at the beginning of the duct indicates that we do see the same sort of structures regardless of fibre concentration.

Wolfgang Bauer Graz University of Technology

I think you just mentioned that you are assuming the turbulence is isotropic in the channel that you are testing. Is this really the case for a headbox where I would assume the turbulence to be anisotropic?

Fredrik Lundell

No, in the headbox you have strained turbulence. Looking at the development of turbulence models for pure water or pure air, you start with isotropic turbulence and then you develop your models and strained turbulence is typically the second case that you try to model. From those results and from that development which has been going on the last 20 years, we know the effects of strain on turbulence pretty well. So, our assumption is that, if we start out with isotropic turbulence, we learn things about the effects of the fibres which we can apply directly to the strained turbulence in a headbox, thanks to work the turbulence people have done in the past.

Ari Kiviranta

I am going to ask you one very practical question. I used to work in R & D but now in production so I do not have anything else but practical questions any more. When you change the consistency and when you change also the fibre type, you say the headbox may react differently. When you design a headbox for, let's say, a liner board, where you have just 100% long fibre furnish, and then, on the other hand, for newsprint with a lot of recycled fibre, a lot of fillers, do your results indicate that the headbox design has to be completely different for the two cases?

Fredrik Lundell

I guess that is something that will be for the next FRC or may be the FRC after that when we can actually apply our results. Perhaps the next FRC will be the development of the models and then in 8 years from now, there might be some indications for actual production headboxes. So, these ought to be viewed as fundamental results in the really basic sense.