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Influence of Design of Turbulence Generator on Flow Behavior in Pilot Headbox

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ABSTRACT

The geometry of headboxes is of great importance in obtaining good formation, even basis weight profile and fiber orientation. Therefore, many attentions have been made to examine the influence of the geometry of headboxes on the flow behavior. In this study, to evaluate flow behavior in headboxes, three types of turbulence generators were examined using pilot headbox. Velocity profiles in MD and CD were measured using a pressure monitoring system and flow in headboxes was visualized by dye injection method. CD velocity profiles at three different locations inside the slice of Type A headbox showed that the velocity increased downstream to slice exit and had a pattern with four humps due to the persisting wall effect of step diffusors. Results from the evaluation of normalized velocity profile and flow visualization showed that L-shaped Type C headbox caused a large pressure drop but it lacked in flow stabilizing ability.

Keywords: pilot headbox, turbulence generator, velocity profile, dye injection, flow stability

1. Introduction

Headbox, which is a critical part of paper machine, strongly influences sheet properties, e.g., basis weight variation, fiber orientation, and formation. Headbox is mainly composed of distributor, turbulence generator and slice and each component plays a unique role. Through a distributor, which we call as a manifold, a dilute pulp stock can be distributed across the width of a papermachine. The functions of the turbulence generator are for: 1) the directional change of the flow which enters the headbox from the side to machine direction; 2) uniform distribution of the suspension over the machine width; 3) generation of a controlled turbulence for breaking up fiber flocs (1). And the slice is used to accelerate the flow speed and deliver a stable and well-dispersed stock jet on the wire. The performance of headbox is determined by a variety of factors such as the flow distribution in MD and CD, fiber

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dispersion and turbulence intensity and scale, which are dependent on headbox geometry and stock concentration. Many researchers have reported the effect of headbox design on paper quality. Soikkanen described that residual variation could be decreased and the formation and runnability could be influenced depending upon design of the flow channel (2). Dahl and coworkers showed that the variations in distributor overflow and local slice bar adjustment affected local main fiber orientation across machine width that resulted in diagonal curl (3). Empirical as well as theoretical efforts to design headboxes that provide high quality sheets have been made. Parker and Hergert reported that a newly designed simultaneous convergence headbox provided good fiber dispersion and stable stock flow with low turbulence (4). Dahl and Weiss developed a new step diffusor with hexagonal cross section as a turbulence generator in the headbox and obtained excellent sheet formation (5). Bubik and Christ showed that the flow of stock through a step diffuser element of optimum design has a more even velocity and turbulence profile than that of fully developed turbulent pipe flow by the experiment using Pitot tube and hot wire anemometer (1). Kallmes examined the characteristics of the discharge flow from both rectifier-roll type headboxes and high turbulence, nozzle type headboxes (6). The research of high turbulence headbox was done by Ryti, Paulapuro and Rath (7). They observed a noticeable increase in z-direction strength for paper produced with the high turbulence headbox. Flow behavior in the headbox or pipe which simulates the channel of headbox can be measured with a Pitot tube, hot film anemometer, LDA (Laser Doppler Anemometer), and so on. Hot film anemometer and LDA have been used for measurement of turbulence intensity and scale (8). Bercel and Shuffler measured turbulence and dispersion phenomenon in a model headbox using LDA and fiber optics probe and concluded that mechanical correlation existed between turbulence characteristics and flocculation index (9). Besides, paper machinery builders have developed unique designs of headboxes and presented the superiority of their design by evaluation of flow behavior. Most of these researches, however, were performed by a few of paper machinery builders in advanced country. To secure the competitive edge in tomorrow's globalized paper industry, it is essentially required to have engineering capabilities to design, develop, and analyze the crucial papermaking equipments.

In this study, therefore, a special attention has been made to examine the influence of the geometry of turbulence generators on the uniformity of velocity and pressure in headboxes. These are of great importance in obtaining good formation, even basis weight profile and fiber orientation. To achieve this purpose pilot headboxes and a pressure monitoring system were constructed. Then the flow behavior was investigated experimentally through velocity profile measurements and flow visualization with dye solution.

2. Experimental

2.1 Pilot headboxes

A pilot headbox consisted of turbulence generators and a slice was designed and constructed to study the flow behavior in the headbox. The schematic diagram of the pilot headbox is shown in Fig. 1. Water stored in a 2 m^3 tank was pumped by a centrifugal pump to the distributor and passed through the flexible hoses to turbulence generator, and ejected through the slice and recirculated. The flow rate from the distributor to the headbox was controlled by adjusting the opening of the return gate valve, and the flow rate from the water tank to distributor was monitored using an ultrasonic flowmeter. The data was transferred from the flowmeter to computer by an RS232 cable. The ultrasonic flowmeter, consisted of a pair of ultrasonic transmitters and receivers and located across the flow conduit, measures the flow rate based on Doppler theory. More specifically, two transmitters, one directed to downstream and the other to upstream, detect the travelling time of the flow to derive flow velocity in the conduit (10).

Distributor rather than tapered manifold was adopted to distribute stock evenly to the full width of the slice. A hole plate was installed inside the distributor to stabilize the flow. A number of holes in step diffusor shape with inlet and outlet diameters of 10 mm and 15 mm, respectively, were bored in the plate. Air pad that exists at the upper part of the distributor plays a role of a pulse attenuator. Air pressure in the distributor was adjusted with an air compressor and it was monitored with a pressure gauge mounted at the top of the distributor. Liquid level in the distributor was measured with a transparent tube mounted on the outside of the distributor. Four flexible hoses were used to connect the outlets from the flow distributor to the turbulence generators of the headbox. This design was found to be very effective in maintaining the constant pressure inside the headbox and eliminating the secondary flow produced when the flow direction changes by 90° as in the conventional manifold. At the outlets of the distributor injection valves were installed to inject a dye solution for visual evaluation of the flow behavior in the step diffusor and slice. Parts of the headbox were connected with flange to facilitate replacement and modification. All parts of headboxes were made with clear plastic to make measurements and visual evaluation easy.

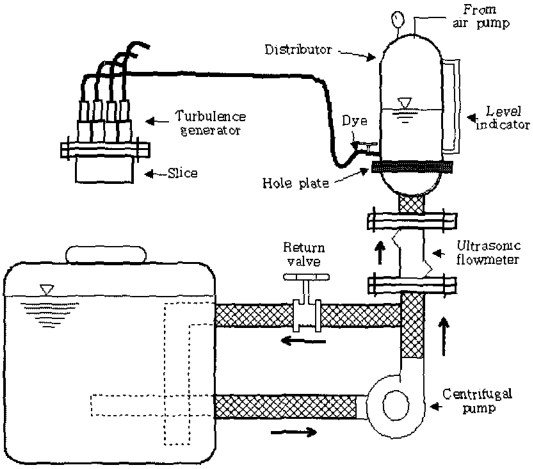


Fig. 1. Schematic diagram of a pilot headbox.

2.2 Design of turbulence generator

In this study three models of turbulence generators - Type A, B, and C - were designed. Type A and Type B were conventional hydraulic headboxes with step diffusor type turbulence generators. And Type C headbox with an L-shaped turbulence generator was designed with an intention to evaluate its applicability as a headbox for high consistency paper machine. The schematic diagrams of headboxes used are illustrated in Fig. 2.

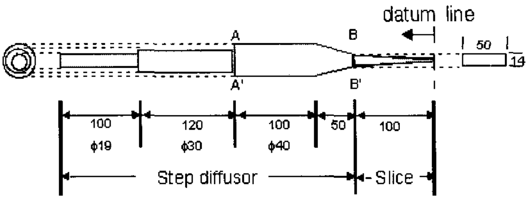
Turbulence generators of Type A and Type B headboxes consisted of three tubes. Two tubes at upstream were circular in cross section. On the other hand the cross section of the third tube gradually changed from circular shape to rectangular shape. The diameters of these three tubes increased from 19 mm, 30 mm, to 40 mm as moves to downstream. Four step diffusors were arranged as shown in Fig.

1 to construct the turbulence generators for a headbox.

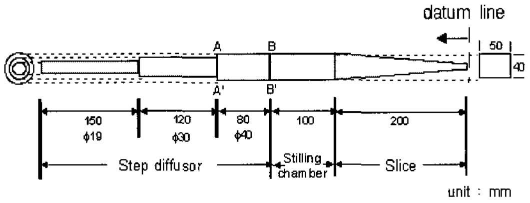
Type A and Type B headboxes differed in both upstream tube lengths and the shape of rectangular outlet of the third tube. The third tube used in turbulence generators for Type A headbox was designed to have the same outlet area as the area of second tube outlet. Thus, the inlet of the third tube was Φ40 mm, and the dimension of rectangular outlet was 50 mm by 14 mm. A simple converging type slice module with an upstream open area of 2800 mm^2 and angle of convergence of 5.7° was mounted to Type A headbox. Both nozzles were tapered over 100 mm length, and slice gap opening was 4 mm.

In the case of Type B headbox, the area of the third tube enlarged from 1257 mm^2 to 2000 mm^2. The outlet of the third tube of Type B headbox was approximately triple times as large as that of Type A. Type B headbox had a stilling chamber of 100 mm long to stabilize the flow. The slice of Type B headbox was also a simple converging type with the angle of convergence of 10.3°. The inlet dimension of the slice of Type B headbox was 206 mm × 40 mm and that of outlet is 206 mm × 4 mm. The length of slice was 200 mm.

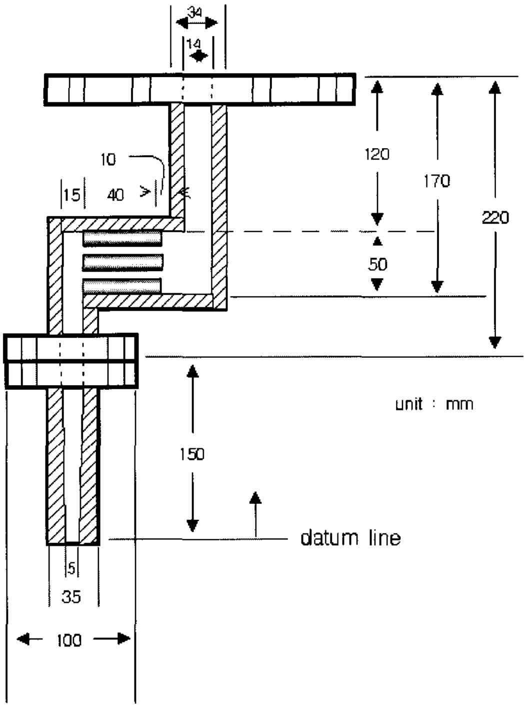
Type C headbox was designed to generate turbulence by turning flow direction and changing the circuit area in the headbox. The direction of flow was turned by 90° and cross sectional area was changed abruptly. The change of flow direction caused a large pressure drop. Slice gap was decreased gradually from 15 mm to 5 mm over 150 mm length. Thus, the angle of convergence was 3.8°. This turbulence generator of Type C was assembled with a step diffusor and slice of Type A headbox.



(a) Type A



(b) Type B



(c) Type C

Fig. 2. Schematic diagrams of three types of turbulence generators.

Type A and C headboxes were installed in vertical direction, i.e., the flow directed downward from the headbox to the storage tank. On the other hand, Type B headbox was mounted horizontally to the pilot headbox system.

2.3 Measurement of velocity

Static as well as stagnation pressures in the slice of the laboratory scale headboxes were determined using a double wall Pitot tube made with two concentrical stainless steel tubes with diameters of 1/16″ and 1/8″. Outer Pitot tube with eight holes around it was utilized to measure the static pressure, and the inner tube with a hole upper front was used to measure the stagnation pressure. Side holes on the outer tube wall were made at a place apart from the Pitot tube tip eight times of outer tube diameter to get fully developed flow. To facilitate the insertion of the Pitot tubes mounted on the traversing system, L-shaped or U-shaped Pitot tubes were utilized. The pressure data detected by Pitot tubes were converted to digital data with a digitizer and collected on a personal computer. The velocity data were obtained using correlation equation that represents the relationship between the stagnation pressure from Pitot tube and average velocity calculated from ultrasonic flowmeter.

To control the CD movement of the Pitot tube in the slice a traversing system was utilized. Traversing system was made up of a stepping motor, reducing gear, and ball screw unit. The deceleration ratio of the reducing gear was 1/18 and available pulse range was 1 to 99999. Motor speed was 40 mm/min. The MD position of pressure measurement was adjusted manually by changing the location of the traversing system. The datum point in MD was located at the end of slice. The data acquisition and traversing system allowed to determine both static and stagnation pressure every 2.5 mm in CD for laboratory pilot headbox.

During the measurement, the fractional opening which was determined by dividing the opening length with the diameter of the valve was kept constant at 0.1. Same experiment was carried out repeatedly for other types of headboxes with different turbulence generators and slices.

2.4 Flow visualization

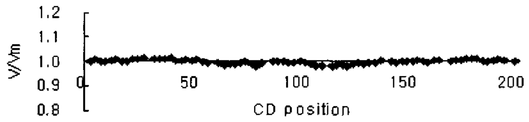
Flow visualization using dye solution has been used to examine the operating physical principles in the headbox. In this study a red dye solution was employed to visualize the flow in the slice and turbulence generator of pilot headboxes. After the dye solution was injected into one of the distributor outlet valves, the flow of the dye solution in the step diffusor and slice was photographed.

3. Results and Discussion

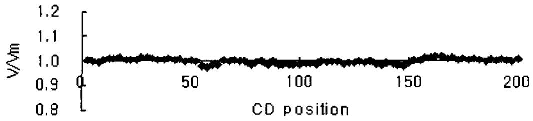
3.1 Flow velocity in headboxes

CD flow velocity in headboxes is affected not only by flow rate but also by headbox geometry. Effect of headbox design on flow velocity was investigated using three types of turbulence generators as shown in Figs. 3 - 5. CD velocity profiles at the different locations inside the slice are depicted.

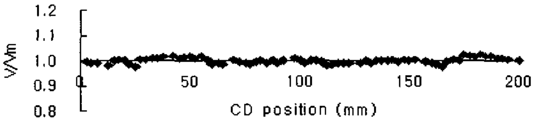
Since the flow velocity varies depending on the types of headbox and measurement points, the velocity was normalized for comparison. The normalization was proceeded by dividing the local velocity (V) at each measuring point with the average velocity (Vm) at the location of measurement. In figures, 'x' means the distance from the slice tip.



(a) 14 mm (x / slice length = 0.140)

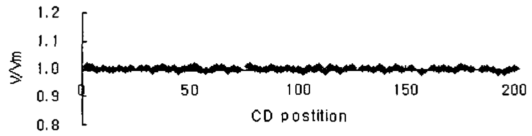


(b) 25 mm (x / slice length = 0.250)

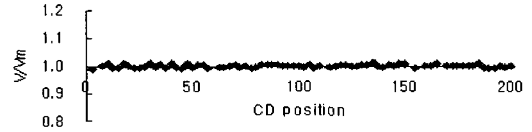


(c) 55 mm (x / slice length = 0.550)

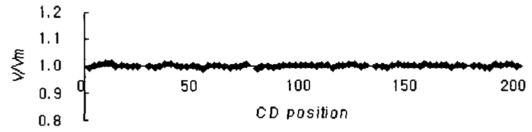
Fig. 3. **CD profiles of the normalized velocity at three different distances from the slice of Type A headbox.**



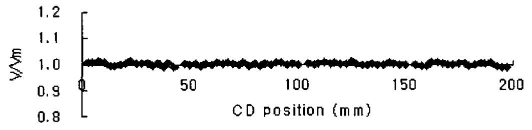
(a) 25 mm (x / slice length = 0.125)



(b) 55 mm (x / slice length = 0.275)



(c) 96 mm (x / slice length = 0.480)

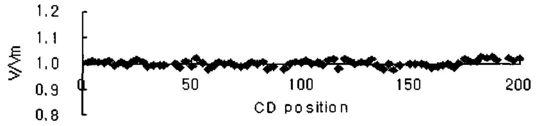


(d) 137 mm (x / slice length = 0.685)

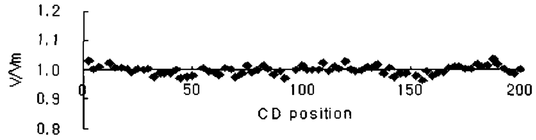
Fig. 4. **CD profiles of the normalized velocity at three different distances from the slice of Type B headbox..**

As the distance from the step diffusor increased, i.e., as the distance from the slice exit decreased, the variation of CD velocity decreased for all types of headboxes. This is most clearly shown for the Type C headbox as seen in Fig. 5. As shown here the CD velocity profile became stable at a place near the slice tip. Uniform CD profile means the flow is stabilized. In other words, the smaller the variation in CD velocity, the more stable the flow is and this would contribute to produce better quality products. Type A and Type B headboxes gave relatively uniform CD profiles, while Type C headbox showed poor CD profile.

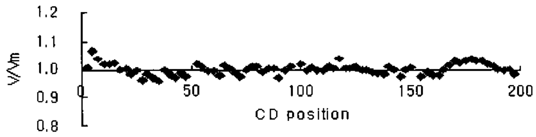
A velocity pattern with four humps was more remarkable in the headbox with Type A turbulence generator than in other types of



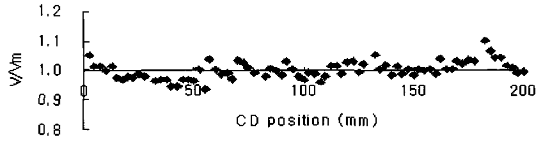
(a) 10 mm (x / slice length = 0.067)



(b) 70 mm (x / slice length = 0.467)



(c) 130 mm (x / slice length = 0.867)



(d) 160 mm (x / slice length = 1.067)

Fig. 5. **CD profiles of the normalized velocity at three different distances from the slice of Type C headbox.**

headboxes and it could be definitely seen as the distance from the step diffusor decreased, i.e., it went to upstream. The hump pattern was caused by the persisting wall effect of step diffusors. Because Type B headbox had a stilling chamber long enough to stabilize the flow and Type C headbox had a long L-shaped channel after step diffusor, the wall effect of the step diffusor was not so clearly observed in Type B and C headboxes as in Type A headbox.

The maximum and minimum values of normalized velocity are shown in Table 1. And the range which is calculated as a percent difference between maximum and minimum values in Table 1 was shown in Fig. 6. The 'relative distance' was obtained by dividing the distance from the slice tip in measuring by slice length. When Type C headbox was employed, there exists wide variation of velocity, i.e., the normalized velocity difference of about 20% was observed. It seemed to be caused by sudden changes of the flow direction. The change of flow direction by 90° accompanies considerable pressure loss. As this pressure loss is directly related with the rate of energy dissipation per unit volume (ε) according to the theory of isotropic turbulence (11), Type C headbox could be considered to provide sufficient pressure loss for improving dispersion of fiber suspension. However, this headbox gave flow patterns that lack in CD velocity uniformity. Type C headbox produced large scale turbulence and this caused unstable flow. Consequently, it is considered that modification of Type C headbox is required to obtain a flow with sufficient turbulence and stability.

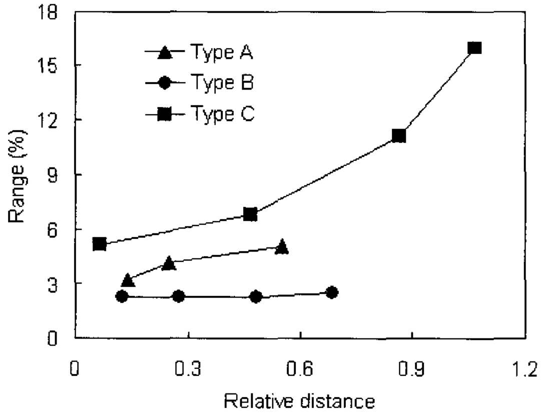


Fig. 6. A range of CD velocity at the different locations in slice.

Table 1. The comparison of maximum and minimum values of normalized velocity in CD profile

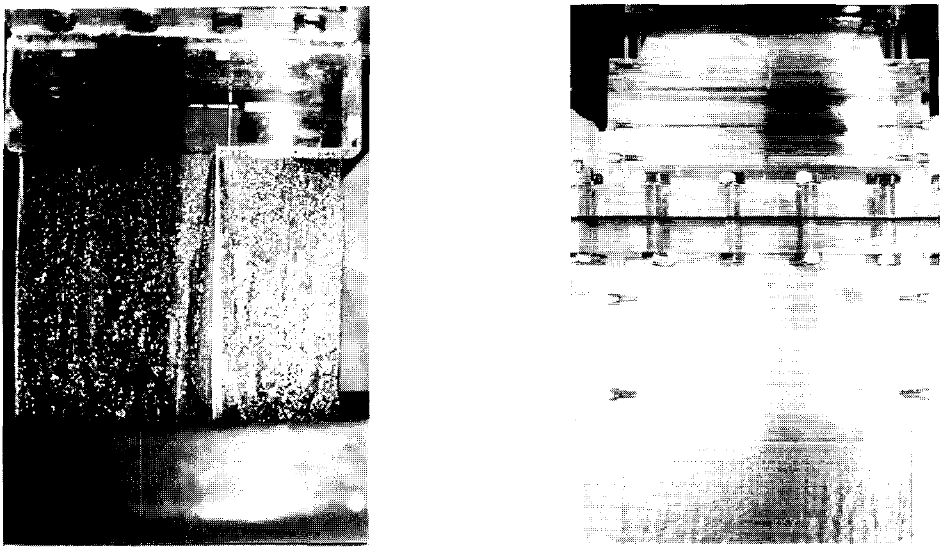
Type	Distance from slice	Maximum	Minimum
A	14	1.0134	0.9812
	25	1.0188	0.9769
	55	1.0257	0.9746
B	25	1.0111	0.9890
	55	1.0105	0.9880
	96	1.0119	0.9897
	137	1.0117	0.9872
C	10	1.0259	0.9742
	70	1.0334	0.9656
	130	1.0684	0.9570
	160	1.0972	0.9371

Therefore, it would be desirable to design the headbox to provide sufficient turbulence for fiber dispersion and to give stable acceleration of the flow in slice or stilling chamber for flow stabilization.

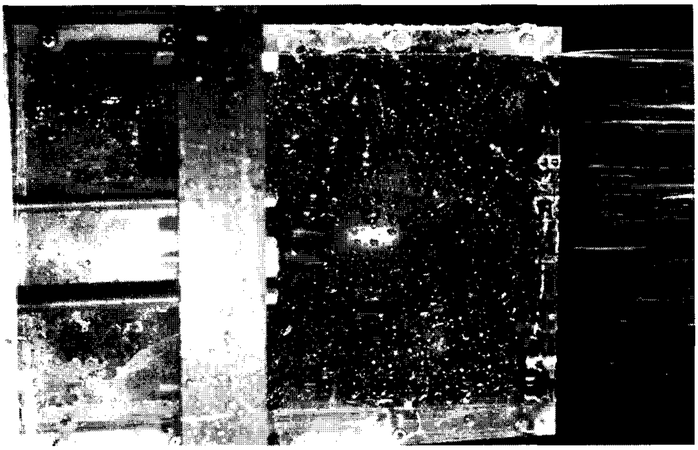
3.2 Flow visualization by dye injection

Flow behavior in the headbox was evaluated after injecting a red dye solution through the valve installed at the distributor outlet. Jet stability and interactions of the flow in the step diffusor and slice for three headboxes were observed.

The intensity and scale of the turbulence which affects the properties of sheets depend



(a) Type A (b) Type C



(c) Type B

Fig. 7. The flow behavior of dye solution in headboxes.

on the design of turbulence generators. The flows in three types of turbulence generators were shown in Fig. 7. As seen here, stable jet was observed in Type A headbox. On the other hand, Type B headbox showed very unstable jet flow which was disturbed by neighboring flow. And this is different from the results of velocity measurements. This result is due to the small scale of secondary flow in CD, which was induced by the tube jets inside the headbox (12). The CD secondary flow causes streaks on the free surface of jet on wire and nonuniform basis weight CD profile. Since the cross sectional areas in turbulence generators for Type

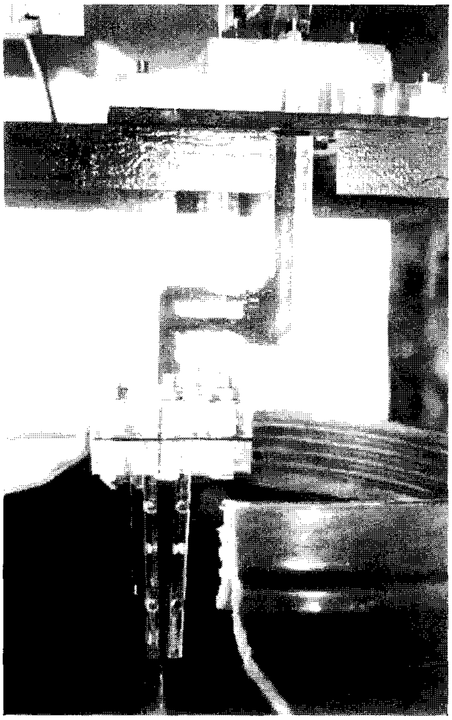


Fig. 8. A side view of the flow in Type C headbox.

B headbox increased successively, jet escaped from the turbulence generator became more unstable due to excessive pressure drops.

Type C also seemed to have a small amount of secondary flow. And it was considered that Type B and Type C headboxes gave a large scale eddies. Although both eddy and turbulence are good for fiber dispersion, their effectiveness decreases with an increase of their scale. Therefore, a sudden expansion of the final cross section of step diffusors had better be avoid.

A side view of the flow in Type C headbox is presented in Fig. 8. It can be seen from Figs. 7 and 8 that large eddies occurred in this headbox especially at corners. It was due to sudden change of flow direction by 90°, which caused a considerable pressure loss. Although a considerable pressure loss is desirable for fiber dispersion, jet flow must be stabilized to obtain uniform velocity profile. In other words, headbox design to bring about large pressure drop with little lateral movement need to be developed for high consistency forming.

Therefore, it is desirable to design the turbulence generator to provide sufficient turbulence without or negligible wall effect. Slice and stilling chamber need to be designed to stabilize and accelerate the flow.

4. Conclusions

To evaluate flow behavior in headboxes with different geometry, three types of pilot headboxes were constructed. As the distance from the step diffusor increased, the variation of CD velocity decreased for all headbox with different types of turbulence generator. But, Type A headbox which don't have a stilling chamber showed that a pattern with four humps due to the persisting wall effect of step diffusors. Results from the evaluation of normalized velocity profile and flow visualization showed that L-shaped Type C headbox caused a large pressure drop but it lacked in flow stabilizing ability. Therefore, it is desirable to design the turbulence generator to provide sufficient turbulence without or negligible wall effect. Slice and stilling chamber need to be designed to stabilize and accelerate the flow.

Acknowledgement

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