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Construction of a Pilot Headbox System and Pressure Monitoring Apparatus for the Development of High Speed Hydraulic Headboxes

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ABSTRACT

To investigate the influence of the design and operating parameters of the headbox on hydrodynamics, a pilot headbox system and pressure monitoring apparatus were constructed. The pilot headbox system consisted of a circulating water reservoir, centrifugal pump, distributor, turbulence generator and slice. The distributor was designed to function as a pressure attenuator. Flow rate to the headbox and MD and CD velocity profiles in the slice zone were monitored using an ultrasonic flowmeter and Pitot tubes, respectively. As the distance from the step diffusor increased, evener CD velocity profile was observed. Wall effect increased with the increase of the velocity. Flow stability in the headbox was evaluated by injecting a dye at the outlet of the distributor. Application of theoretical analysis based on CFD in designing headboxes is briefly discussed.

Keywords *: Headbox, Pressure monitoring, Velocity Profile, Slice*

1. Introduction

Paper machine speed, which has increased substantially during last several decades, is expected to increase continuously in the future even though the increase rate will a bit diminish. Increase of paper machine width, however, does not appear to take place within next ten years. (1-2) To facilitate the increase of machine speed, many open draws have been eliminated and diverse new concepts of compactness have been adopted in designing today's paper machines. The philosophy of compactness in designing today's paper machines can also be found in headboxes, which is one of the most critical parts of a paper machine. Diverse research efforts have already been made to develop headboxes which would provide excellent runnability and product quality.

The importance of headbox design for sheet properties including formation, fiber orientation, MD and CD basis weight uniformity, etc has been acknowledged for many years. (3-4) With technological trends of increasing paper machine speed and reducing basis weight, however, the head-

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box becomes even more important and is regarded as an extremely critical part of the paper machine. And many technological renovations have been made to improve its capability. For instance, the deterioration of fiber orientation that occurs when controlling CD basis weight by adjusting the slice gap has been resolved with the emergence of a dilution headbox. (5) And improved deflocculation of fiber flocs in the headbox were made possible with the development of step diffusors or perforated plate. (6-7) These developments of cutting edge technologies have been made mostly by paper machinery builders in advanced countries, which remains the domestic paper machinery industry lacks far behind in technology. To overcome this technological deficiency extensive research efforts in theoretical as well as experimental aspects should be made.

In this study, a special attention has been paid to examine the influence of the geometry of the turbulence generator and slice on velocity and pressure uniformity in the headbox. These are of great importance in obtaining good formation, even basis weight profile and fiber orientation. To investigate the effect of the design parameters of the turbulence generator and slice on hydrodynamic behavior, analytical as well as experimental approaches have been made.

2. Experimental

2.1 Construction of pilot headbox

A pilot headbox consisted of turbulence generators and 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

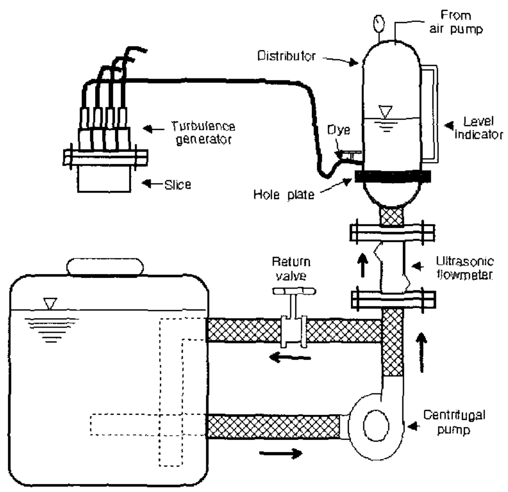

Fig. 1. Schematic diagram of pilot headbox and pressure monitoring system.

pump to the distributor and passed through the flexible hoses to step diffusors, and ejected through the slice and recirculated. The detailed specifications of the tank and pump are shown Table 1 and 2. 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 attenuator was monitored using an ultrasonic flowmeter.

Distributor rather than tapered manifold was adopted to distribute stock evenly to the full width of the slice as shown in Fig. 2. A hole plate was installed inside the distrib-

Table 1. Specifications of the reservoir tank used in constructing the pilot headbox

Item	Description
Material	Elpai
Capacity	2 m^3
Outlet diameter	65 mm
Inlet diameter	65 mm
Overflow diameter	20 mm
Fresh water inlet diameter	15 mm
Drain diameter	25 mm

Table 2. Specifications of the fan pump used in constructing the pilot headbox

Item	Description
Power	220 V, 3 phase, 7.5 HP
Maximum flow rate	1400 L/min
Material	Stainless steel (STS-304)
Type	Centrifugal (Non-clog)
Inlet diameter	65 mm
Outlet diameter	80 mm

utor to even up the flow instability. Air pad that exists at the upper part of the distributor functions as a pulse attenuator. Air pressure in the distributor was adjusted with an air compressor and monitored with a pressure gauge mounted at the top of the distributor. Liquid level in the distributor were measured with a transparent tube mounted on the outside of the distributor. Four flexible hoses were used to connect the flow distributor and 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 conventional manifold. At the outlets from the distributor injection valves were installed to inject a dye solution for visual evaluation of the flow behavior in the step diffusor and slice.

The headbox was made with clear plastic to facilitate measurements and visual evaluation. A step diffusor consisted of three tubes as a turbulence generator was used (Fig. 3). 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. And the dimension of rectan-

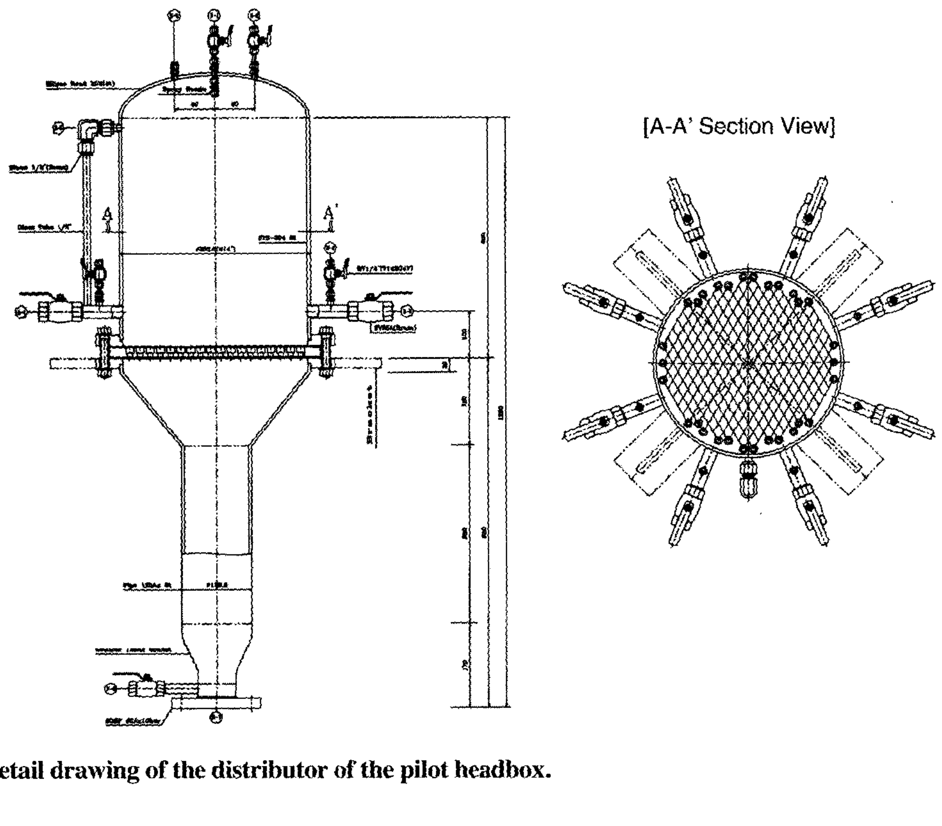

Fig. 2. Detail drawing of the distributor of the pilot headbox.

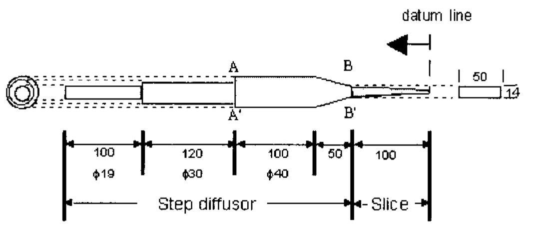

Fig. 3. Schematic diagram of turbulence generator and slice.

gular 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. Both nozzles were tapered over 100 mm length, and slice gap opening was 4 mm.

2.2 Installation of pressure monitoring system

Static as well as stagnation pressures in the slice of the pilot headbox were determined using a double wall Pitot tube made with two concentrical stainless steel tubes. 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. Stainless steel tube with diameters of 1/16" and 1/8" were used as Pitot tubes in this experiment. It was possible to put the tube inside the slice for making measurements in diverse locations both in machine direction and cross machine direction. The pressure data detected by Pitot tubes were converted to digital data with a digitizer and collected on a personal computer. A simple but very effective software for data processing were developed and used.

2.3 Calibration of Pitot tube

To find the relationship between the pressure indicator values acquired using the Pitot tube and data acquisition system and mean velocity of flow in the slice, average pressure indicator values were obtained at different levels of the return valve opening. The average velocity was calculated by dividing the flow rate measured with an ultrasonic flowmeter by the cross sectional area at which the measurement was made. A linear relationship has been found

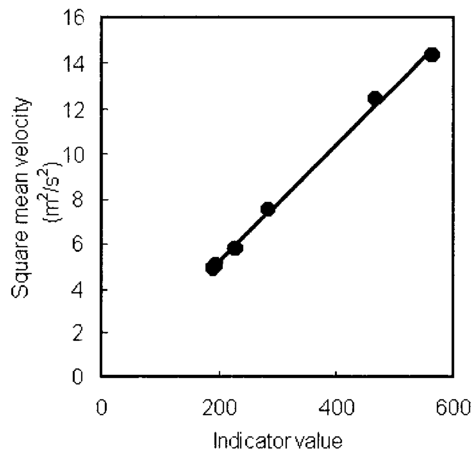

Fig. 4. Relationship between the mean velocity and indicator values of stagnation pressure obtained form the pressure monitoring system.

between the stagnation pressure indicator value and square average velocity as shown in Fig. 4. This indicates that the flow fits well to Bernoulli relationship. Reynolds number for the flow examined in this experiment was greater than 5000. (8) The relationship shown in Fig. 4 was used in converting the pressure indicator value to flow velocity.

2.4 Measurement of pressure and velocity

To control the CD movement of the Pitot

tube in the slice a traversing system was utilized. The position of pressure measurement in MD was adjusted manually by changing the location of the traversing system. The datum point in MD was located at the end of the slice. The data acquisition and traversing system allowed to determine both static and stagnation pressure every 2.5 mm in CD.

Water rather than stock was used in this experiment and a return valve was used to control the flow rate from the pump to distributor. Depending on the fractional opening of the return valve, flow velocity was changed. Pressure and velocity were measured as a function of the fractional opening at a given MD position over the full width of the slice. The fractional opening was determined by dividing the opening length by the diameter of the valve.

3. Results and Discussion

3.1 Effect of the fractional opening of the return valve

The flow rate from the distributor to headbox was controlled by adjusting the opening of the return gate valve in this experiment. Mean velocities at three different locations in the slice were evaluated as a function of the return valve opening and illustrated in Fig. 5. As shown here the average velocity decreased abruptly as the valve opening increased from 0.1 to 0.5. When the valve opening was less than 0.1 or greater than 0.5, the mean velocity decreased rather slowly. It is because substantial contraction of open areas and increase of frictional loss occurred when the return valve opening ranged from 0.1 ~ 0.5. The fact that only minor reduction in velocity was observed when the opening ratio of the return was high indicated a small frictional loss occurred in the return flow line.

Mean velocity increased as the measurement distance from the slice tip decreased. The increment ratio, however, was rather small indicating significant friction loss accompanies the flow in the slice and hoses connecting the distributor and headbox.

In Fig. 6, CD velocity profiles at three different locations inside the slice are depicted. Measurements were made at 25mm, 40mm and 55mm away from the end of the exit of

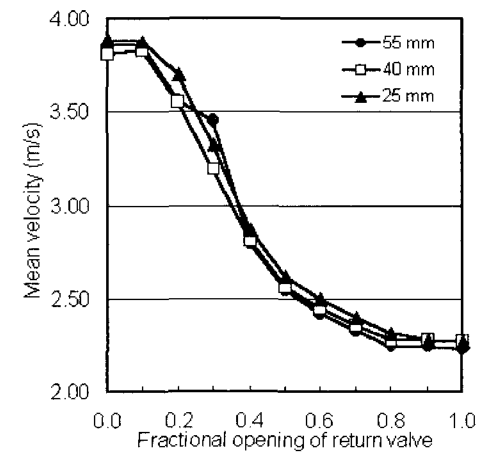

Fig. 5. Mean velocity at different positions from the slice vs. fractional opening of the return valve.

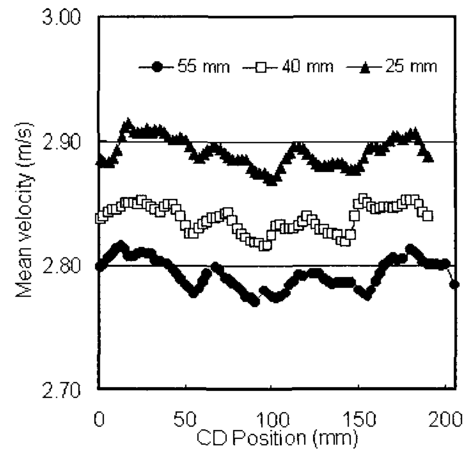

Fig. 6. CD velocity profiles at three different locations in the slice.

slice toward the step diffusor. Here the fractional opening of the return valve was kept constant at 0.4. As seen here the flow velocity increased as the distance decreased, i.e., as the cross sectional area of the slice decreased. A velocity pattern with four humps was observed. This suggested complete uniformity of flow was not obtained

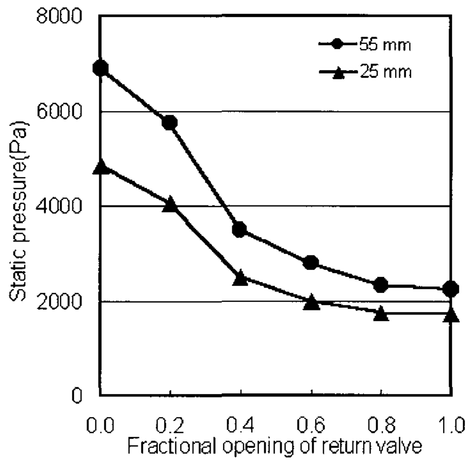

Fig. 7. Static pressure at different positions from the slice vs. fractional opening of the return valve.

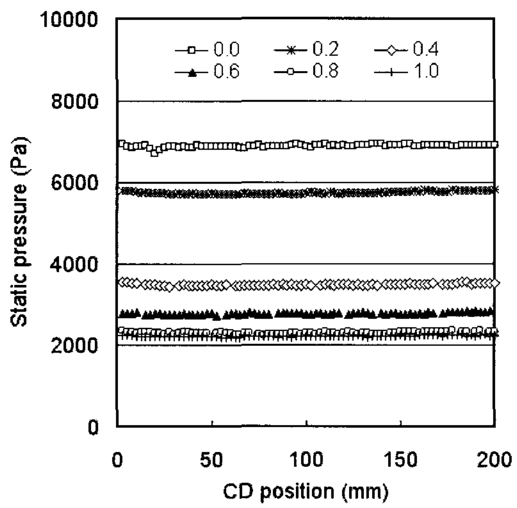

Fig. 8. CD profiles of the static pressure at 55 mm apart from the slice.

due to the persisting wall effect of step diffusors. The CD velocity difference, however, was only 1 ~ 2 % of the mean velocity. More intense velocity fluctuation was observed when the mean velocity was low. The wall effect of the step diffusor decreased as the distance from the step diffusor increased, that is, stable flow velocity profile could be obtained. Stability of velocity profile is one of the most important requirements in headbox design, and if this lacks undesirable fiber orientation will result. The hump patterns got stronger as the flow rate increased by reducing the fractional opening of the return valve.

Effect of fractional opening on average static pressure is shown in Fig. 7. When the opening ratio increased from 0.0 to 0.4 abrupt reduction in static pressure was observed. When the opening ratio increased further, however, rather small reduction in static pressure was noticed as the mean velocity depicted in Fig. 5. Static pressure decreased as the measurement distance from the slice tip decreased. This indicates that as the cross sectional area became smaller with reduction of the distance from the slice, static pressure was converted to velocity.

CD static pressure profile at 55 mm apart form the outlet of slice was represented in Fig. 8. It was quite uniform over full width of headbox.

3.2 Flow visualization by dye injection

To visualize the flow, smoke, helium bubbles or dust particles have been employed as mark substances in aerodynamic and hydrodynamic researches. A variety of dyes and hydrogen bubbles are also being used. (9) In this study a red dye solution was employed to visualize the flow in the slice and turbulence generator of the pilot headbox. Flow behavior in the headbox was evaluated after

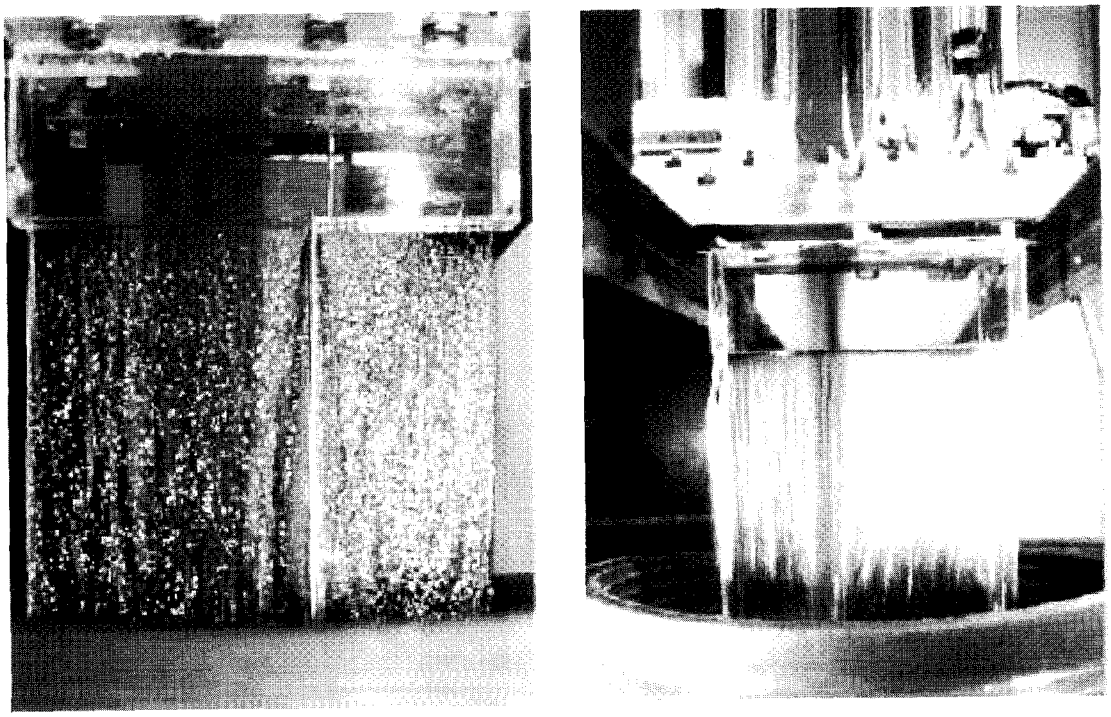

Fig. 9. Photographs of jet with equal flow rate (left) and unequal flow rate (right) in four step diffusors.

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 were observed. When the flow rates through four step diffusors were adjusted to be equal, the flow in the headbox appeared very stable and no strong jet interaction was observed. When the flow rate in one of the step diffusors was changed, however, extensive CD flow in the headbox as well as jet instability was observed as seen in Fig. 9. This suggests that when the adjustment of slice gap was made to control CD basis weight profile, secondary flow would be generated, which in turn causes jet interaction, streak, and deterioration of the fiber orientation.

3.3 Theoretical analysis

Theoretical analysis of flow is indispensable for designing next generation of high speed paper machines. Theoretical approach could be adopted not only to evaluate the effect of design parameters on velocity profiles but also to investigate their influence on turbulence scale and intensity. Navier-Stoke equation and CFD are most frequently used for theoretical analysis of the fluid flow. The analytical methods such as FEM, FDM, and spectral element method are commonly used.

A spectral element method was used in

Table 3. Flow and numerical conditions for theoretical analysis

Working fluid	water
Kinetic viscosity, ν (m^2/s)	1.0068×10^{-6}
Inlet velocity, Uin (m/s)	7.266
Inlet diameter, Di (mm)	19
Reynolds number, Re	$\approx$137,120
Exit section, width $\times$ height (mm^2)	50 $\times$ 14

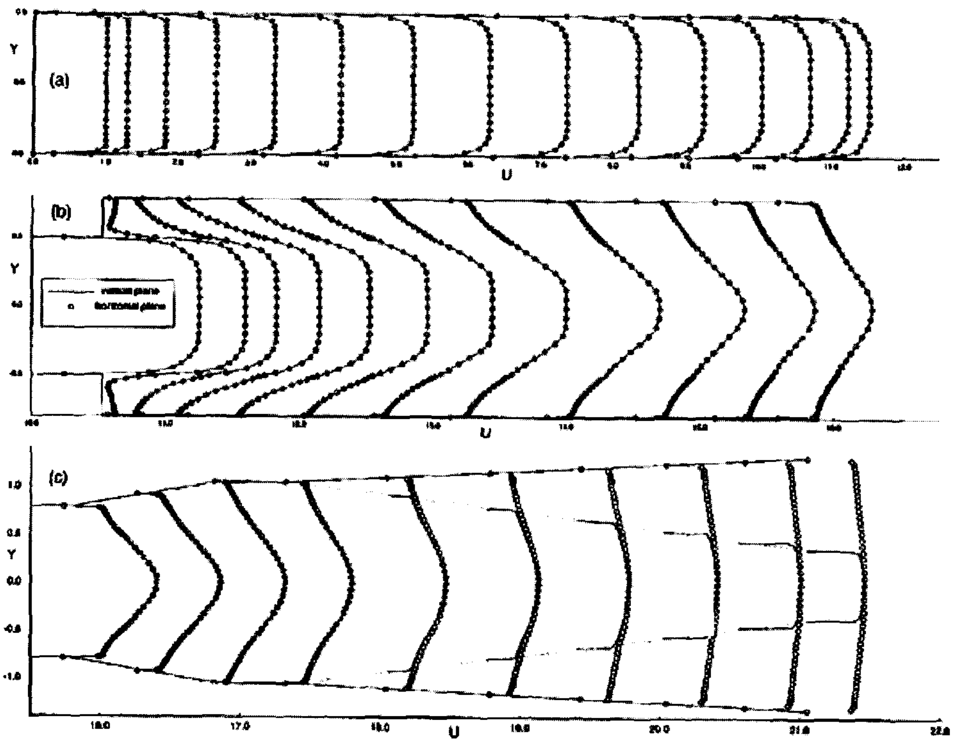

Fig. 10. Variation of profiles of streamwise velocity at symmetric plane. (a) before expansion; (b) and (c) after expansion.

this study to investigate the velocity profile in a step diffusor. Flow and numerical conditions used in spectral elemental analysis of velocity profiles are listed in Table 3. The step diffusor tube begins as a conventional circular tube followed by a sudden expansion to a second circular section, and this is followed by a smooth accelerating transition to a rectangular outlet. Velocity profiles in this step tube are shown in Fig. 10.

Fig. 10 (a) shows that the flow velocity profiles in the first circular tube are perfectly symmetrical. The fluid stream separates from the wall and issues as a jet into the enlarged section when the cross section of the diffusor tube is suddenly enlarged as illustrated in Fig. 10 (b). The velocity profile in the second enlarged tube was symmetrical as well, and it became flatter as the flow proceeds in the expanded tube. When the circular cross section of the step diffusor changes into rectangular shape at the second stage of expansion, CD velocity uniformity and stability were enhanced (Fig. 10 (c)). This shows a shape change that is not accompanied by cross sectional area enlargement is very effective to achieve CD velocity uniformity.

As depicted in Fig. 6, however, the flow at the exit of the step diffusor showed turbulent characteristics. It is needed, therefore, to refine the flow conditions for detailed analysis of the flow.

4. Conclusions

MD/CD velocity profiles in the pilot headbox were evaluated using pressure monitoring apparatus. When the fractional opening of the return valve increased from 0.1 to 0.5 abrupt decrease in the average velocity was observed. CD velocity profiles became evener and faster at the downstream from step diffuser with only minimal wall effect. It was verified from dye injection experiments, stable jet without jet interaction could be obtained. On the other hand when the flow rates in step diffusors were different, CD flow and jet interaction occurred. These unstable jet would cause the deterioration of paper properties.

Theoretical analysis based on CFD showed that the design of step diffusor would give excellent CD velocity uniformity. Especially the shape change of the tube with no cross sectional area enlargement from circular to rectangular was very effective in this regard. To optimize headbox design, more detailed theoretical analysis needs to be made.

Acknowledgement

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