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Flow Control of a Hydraulic Headbox of Papermaking Machines

M. Sumida and S. Suzuki

***Abstract*—An experimental study of the flow in a modeled hydraulic headbox of papermaking machines was performed. The turbulent boundary layer generated on the partition plate in the dispersion part and the wakes formed downstream of the plates were investigated by the flow visualization technique using a smoke wire method and by hot-wire measurement. Control of the flow characteristics was examined in a combination of two types of channel and four types of inserted plate that differ in convergence and trailing edge shape, respectively. As a result, rectification by contracting the channel is effective in realizing a uniform time-average velocity distribution and in reducing and unifying turbulence intensity. Furthermore, the uniformalization of the time-average velocity distribution is high for the trailing edges of tapered and wavy shapes; however, one of the turbulence intensities is excellent for the tapered edge.**

***Index Terms*—flow control, headbox, flow visualization, wake, convergent channel.**

I. Introduction

THE purpose of this study is to investigate the flow field from the dispersion to the rectification sections of a modeled hydraulic headbox of a papermaking machine. To this end, we carry out a visualization experiment and a velocity measurement on the turbulent boundary layer generated on a partition plate and wakes formed downstream of the plate. We examine the flow characteristics for various trailing edges of the plate inserted in two types of channel and study their control.

A papermaking machine consists of five parts: a headbox, a wire, a press, a dryer, and a calender and reel. The headbox, from which pulp suspension is jetted out, as shown in Fig. 1, is the most important part for papermaking. It controls the flocculation of pulp fibers and jets out pulp liquid in a state of uniform concentration of pulp fibers, as much as possible. Therefore, to rectify the raw material discharged from a pump in the headbox and to uniformly divide it in the direction of the width, improvement examination has been carried out up to now. Thus, the structure of the headbox has undergone through many changes [1, 2]. A hydraulic-type headbox is one of them and has distributors and partition plates (Fig. 1). The distributors assign the pulp liquid in the width direction. Subsequently, the pulp liquid is distributed by the partition plates inserted in the channel and is rectified through passages. In such a way, the pulp liquid not only prevents the worsening of fiber dispersion, but also makes the orientation uniform.

The dispersion and jetting-out parts in the headbox are modeled as a flow field in which the flow along the inserted plate is accelerated owing to the contraction of passages from the vicinity of the trailing edge. With regard to this flow problem, in general, there have been many fundamental studies so far. For example, for the wake near the trailing edge, Toyoda & Hirayama (1973) studied the transition process from the turbulent boundary layer before the trailing edge to its wake [3]. Furthermore, for the wake in the contraction channel, Prabhu & Narasimha (1972) investigated a two-dimensional wake under a pressure gradient [4]. However, the above previous studies are fragmentary from the viewpoint of useful information about improving the dispersion part passages of the headbox. Therefore, it is necessary to obtain basic information on flow characteristics for the headbox to improve performance.

In this paper, considering the above-mentioned circumstances, we deal with the flow problem of a wake downstream of a partition plate, with several trailing edge geometries, inserted in both linearly and smoothly convergent channels. The flows were visualized by the smoke-wire method and velocity measurement was performed with a hot-wire anemometer. Thus, knowledge of their characteristics obtained becomes a clue to improving the headbox.

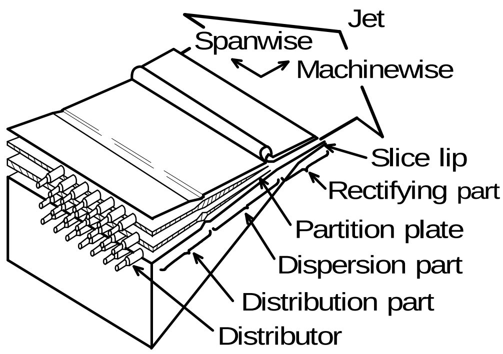

Fig. 1. Structure of hydraulic headbox of papermaking machine.

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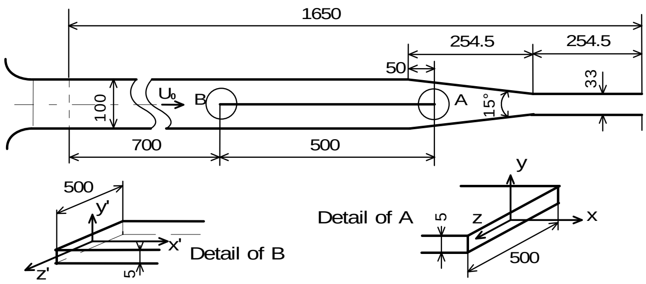
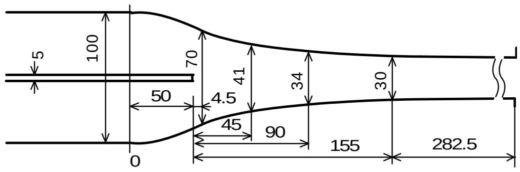
II. Experimental Apparatus and Procedures

A. Experimental Apparatus

A schematic diagram of the channels employed in this experiment and the geometry of the partition plates inserted in them are shown in Figs. 2 and 3, respectively. The dimensions were based on those of a certain practical papermaking machine, that is, the configurations were about three times as large; they were made of transparent acrylic plates. The width of the passages was 500 mm. The apparatus was of the suction type, in which the right end of the channels was connected to a blower controlled by an inverter. Moreover, to examine the effect of channel convergence on the flow characteristics of the wake behind the inserted plate, a similar experiment was performed on the parallel channel. The length and thickness, *d*, of the plates were 500 and 5 mm, respectively.



(a) Linearly convergent channel.



(b) Smoothly convergent channel.

Fig. 2. Test channel (side view, unit mm).

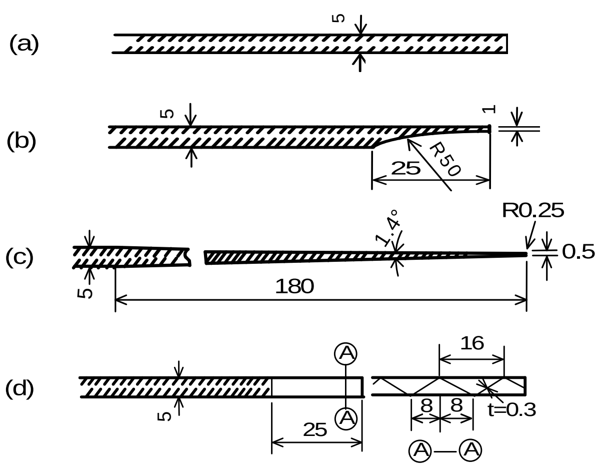


Fig. 3. Configuration of trailing edge of partition plate (unit mm). (a) Rectangular shape, (b) R-shaven shape, (c) Tapered shape, (d) Wavy shape.

Four trailing edge shapes, as shown in Fig. 3, were employed to investigate the relationships between fiber dispersion and the turbulence and vortex structure of the wake. For the rectangular shape in Fig. 3(a), a separated shear layer is formed. For the R-shaven shape in Fig. 3(b), it is considered that longitudinal vortices occur with greater ease than for the rectangular shape. Furthermore, the plate with a taper angle of about 4° in Fig. 3(c) corresponds to that employed in an actual headbox. On the other hand, for the wavy shape in Fig. 3(d), three-dimensional longitudinal vortex streets are induced and this implies the effects of promoting the diffusion of the wake.

The coordinate system is shown in Fig. 2(a). Here, the origin of the coordinates is the center of the edge of the plate. The *x*-axis is in the stream direction and the *y*-axis is in the direction perpendicular to the stream and plate, whereas the *z*-axis is in the spanwise direction.

The cross-sectional average velocity at the entrance was U_0=3 m/s. These give a Reynolds number $U_0 d/\nu$ of 940, with ν being the kinematic viscosity of air. Under these conditions, the boundary layer near the trailing edge of the plate can be considered to be in a nearly fully developed turbulent state (Tani et al., 1977) [5]. The flow in the region downstream of *x*=–200 mm was the subject of the measurement.

B. Flow Visualization and Velocity Measurement

Flow was visualized by the smoke wire method. The wire used was a stainless steel line of 0.1 mm diameter, to which oil with silver powder was added. The fluid layers to be rendered visible were illuminated with a sheet light of 8 mm thickness from 3–6 stroboscopes. The boundary layer on the plate and the wake were visualized. The flows in the vertical, horizontal and cross-sectional planes parallel to the *x*–*y*, *x*–*z* and *y*–*z* planes, respectively, were photographed with a Nikon FE2 camera at a shutter speed of 1/60.

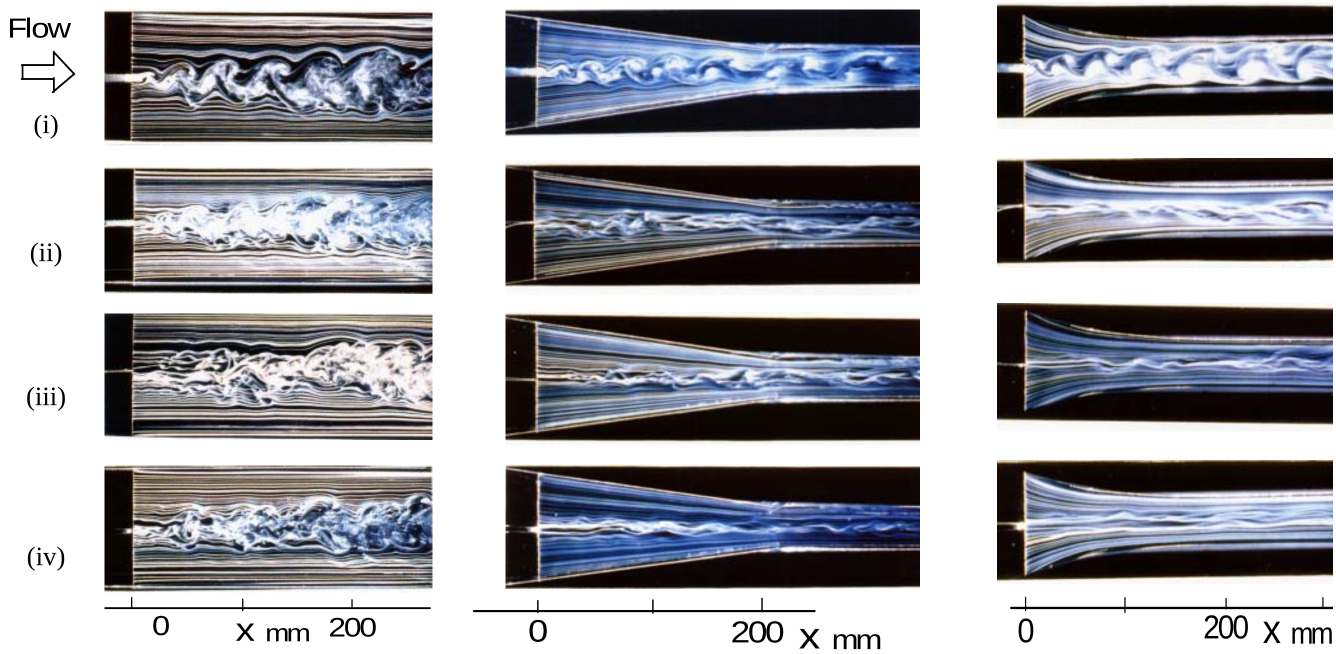
Velocity measurement was performed using a hot-wire anemometer with an I-type probe. The time-average *U* and the turbulence intensity u_{rms} of the velocity *u* in the stream direction were obtained. The measurement on the *y*-axis was executed at 5 stations of *x*=–100, 4.5, 45 and 205 mm for the smoothly convergent channel and of *x*=–100, 4.5, 45 and 240 mm for the linearly convergent and parallel channels. On the other hand, the velocities on the *z*-axis were obtained at stations of *x*=45 and 90 mm.

III. Results and Discussion

A. Visualization of Flow Pattern

Photographs of the wake downstream of the trailing edge of the plate inserted in the parallel, linearly and smoothly convergent channels are shown in Fig. 4. For the side view, the smoke wire was set at *x*=1 and *y*=0 mm, immediately behind the trailing edge. The flow condition is that the Reynolds number defined as $U_m d/\nu$ is about 10^3, where U_m is the cross-sectional average velocity. The value almost corresponds to that of a headbox of a practical papermaking machine.

From the visualization, we can summarize our findings as follows: i) it is difficult to restrain the generation of a vortex street observed behind trailing edges such as a rectangular shape by means of converging the channel; ii) a smoothly



(a) Parallel channel. (b) Linearly convergent channel. (c) Smoothly convergent channel.

Fig. 4. Flow patterns of wake (side view: *x-y* plane).
(i) Rectangular shape, (ii) R-shaven shape, (iii) Tapered shape, (iv) Wavy shape.

convergent channel has a higher rectifying effect for a wake than other channels because the acceleration parameter is large near a trailing edge; iii) for both tapered and wavy edges, in particular, there are significant effects against reducing and rectifying a wake in converging channels.

Furthermore, for practical use, it is important for the headbox to display its full abilities on where the trailing edge should be set in the convergent channel. That is, it is necessary to adopt a partition plate, at the trailing edge of which turbulence factors are hardly produced, such as in the case of the tapered and wavy edges. In addition, it is required that the turbulent boundary layer reduces its thickness by the contraction and acceleration of the fluid upstream of the trailing edge. Thus, when streams separated by the partition plate smoothly flow together behind the trailing edge of the plate, one can anticipate obtaining a uniform velocity profile and attenuating turbulence. On the other hand, for the rectangular shape, although obtaining a uniform velocity profile was attempted by the convergence of the channel, the accelerated flow field becomes a stream more strongly separated at the trailing edge. Therefore, the rectifying effect cannot be anticipated.

B. Mean Velocity and Turbulence Intensity

On the basis of the flow observation stated above, velocity measurement was conducted to further examine the effects of the configuration of the trailing edge and of the convergence of the channel quantitatively. The rectangular, tapered and wavy shapes were chosen as trailing edge shapes in this research. Figure 5 shows profiles of the mean velocity U and the turbulence intensity u_{rms} on the z-axis, in the central plane of y=0 mm, in the linearly convergent channel. At x=45 mm, the mean velocity for the tapered edge shows a profile with a

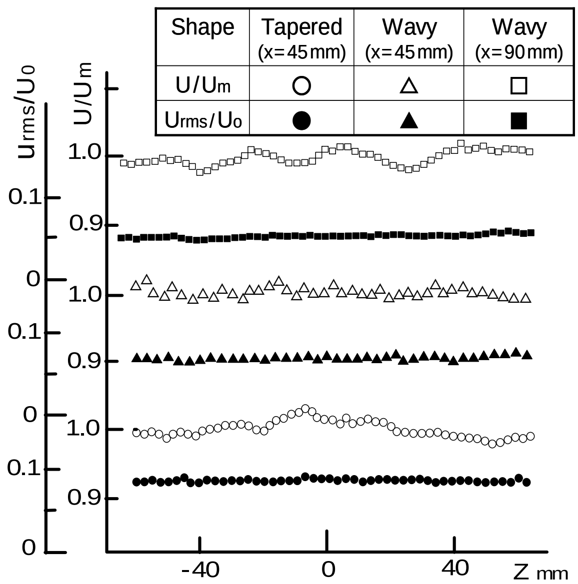


Fig. 5. Distributions of mean velocity and turbulence intensity at center of wake in linearly convergent channel.

small undulation. For the wavy edge, on the other hand, U exhibits a profile like a sawtooth waveform, of which the ruggedness corresponds to 1/2 intervals of the pitch for the wavy shape. However, the mean velocity at x=90 mm shifts to a profile with an undulation of about twice the pitch.

The changes in the flow characteristics of the wake along the x-axis are shown in Figs. 6 and 7. In the figures, the turbulence intensity u_{rms} and the mean velocity U_c on the

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centerline of the channel, i.e., the *x*-axis, are displayed, respectively. Here, u_{rms} is divided by the cross-sectional average velocity U_0 before the partition plate. Also, U_c is nondimensionalized with the local main flow velocity U_e in each plane. Their descriptions are schematically shown in Fig. 7.

First, we show a general view of the characteristics of the parallel channel in Figs. 6(a) and 7(a). For the rectangular shape, vortices, on the plate thickness order, separated at the corners of the edge, are formed at $0<x\leq 6$ mm in the shear layer. Hence, the velocity U_c at x=4.5 mm takes a negative value with a magnitude of about one-tenth of the velocity U_e, and the turbulence intensity is also weak. However, just downstream, the flow is accelerated to turn in the *x*-direction. Then, the turbulence intensity rapidly increases to its maximum at $x\approx 30$ mm, where Karman's vortex street is developed. After that, it decreases along the *x*-axis. On the other hand, for the tapered and wavy shapes, the separated shear layer is so weak that the flow immediately behind the edge is enhanced, without flowing backward, in the *x*-direction. This is because the thicknesses of the trailing edge are 0.3 and 0.5 mm, which are small. The turbulence intensities are almost equivalent to each other, and they gradually decrease from 8% near the trailing edges. Downstream of x=240 mm where velocity was measured, there is no wide difference between the two shapes and the rectangular shape in velocity. In addition, the turbulence intensities at x=45 mm for the tapered and wavy shapes indicate about three quarters of that for the rectangular shape. The reason for the tapered shape is that the separated shearing layer is weak. For the wavy shape, the flows towards the dents of its waveform interfere with the wake so that the vortices separated at the trailing edge become weak and the formation of the lateral vortex street is inhibited. For the reasons mentioned above, it is considered that the turbulence intensities are reduced.

Clearly, there is no effect of the trailing-edge configuration on the half width *b* of the wake. 2*b* increases approximately in proportion to $x^{1/2}$ from *d* of about 5 mm, since the region of the velocity defect near the trailing edge becomes approximately as thick as the plate. However, the wake is controlled by the walls from $x\approx 150$ mm with the result that its expansion ratio is decreased gradually. The figure is omitted.

Next, we discuss the effects of the channel convergence on the wake characteristics. When the channel converges with the result that the flow is contracted, the number of velocity defects is reduced, promoting the flattening of the velocity profile. This causes turbulence intensity to decrease and the flow is rectified. Furthermore, in the linearly convergent channel, the wake does not extend downstream of $x\approx 100$ mm. For the smoothly convergent channel, on the other hand, the flow loses its feature as a wake since the centerline velocity on the *x*-axis almost recovers to the local main-flow velocity.

We shift our attention to the effects of the configuration of trailing edges. For the wavy shape, the change in turbulence intensity depending on the convergent channel is comparatively small. For the tapered shape in the smoothly convergent channel, turbulence intensity takes its maximum near x=30 mm and decreases thereafter, since the highly separated shearing layer is strongly produced by the rapid acceleration of the fluid. In addition, the velocity defect of the wake in the smoothly convergent channel almost disappears at $x\approx 30$ mm. Nevertheless, for the rectangular shape, the turbulence intensity in the smoothly convergent channel becomes higher than that in the parallel channel. That is, the rectifying effects of converging the channel bring about counterproductivity. The reason for this is as follows. When

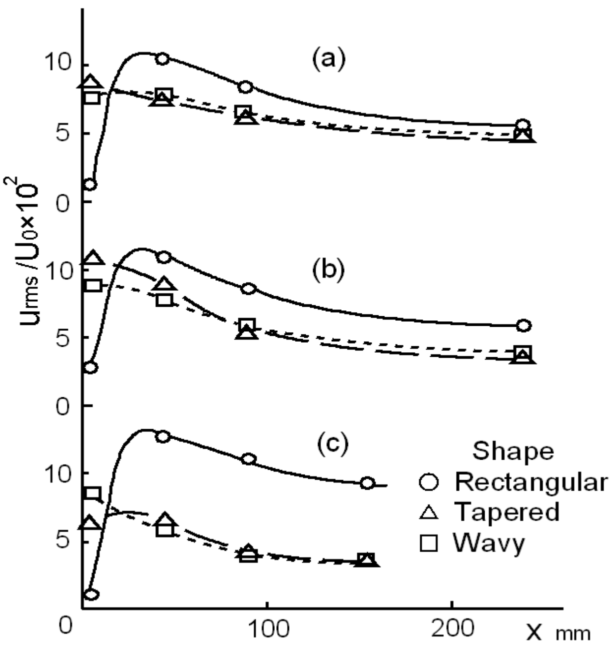

Fig. 6. Turbulence intensity u_{rms} on *x* -axis.
(a) Paralell channel, (b) Linearly convergent channel, (c) Smoothly convergent channel.

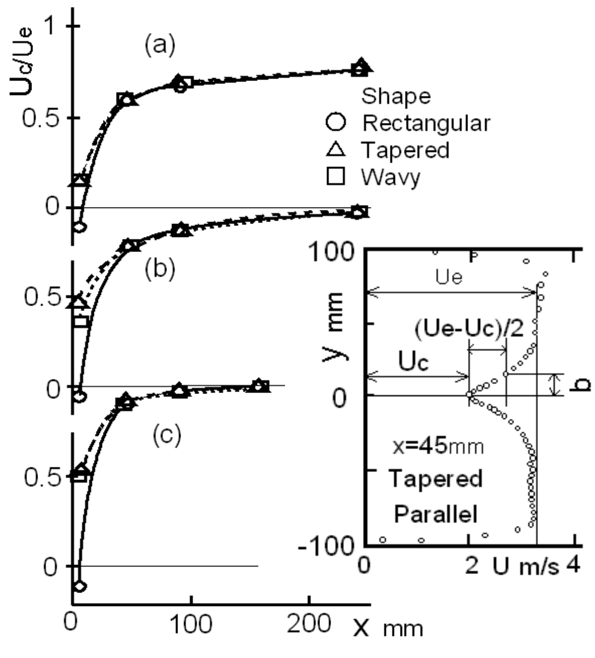

Fig. 7. Change in the number of velocity defect along *x*.
(a) Paralell channel, (b) Linearly convergent channel, (c) Smoothly convergent channel.

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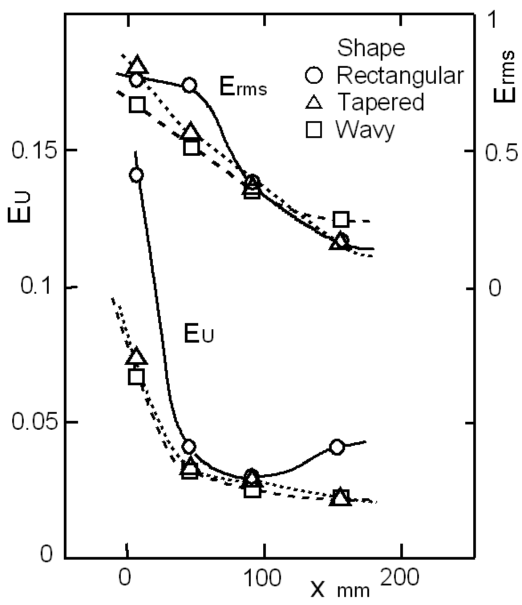

Fig. 8. Uniformities of mean velocity and turbulence intensity for smoothly convergent channel

the acceleration is too large, the vortex separated at the trailing edge of the rectangular shape intensifies and the half-width also decreases. Therefore, a high-shearing layer is formed near the channel axis so that a new turbulence is produced.

In an actual papermaking machine, it is desirable to improve the surface properties of paper such that the distributions of average velocity and turbulence intensity are uniform on the *y*-axis. Moreover, the pulp liquid of the raw material should be sent accelerated at a certain degree from the headbox to the wire part. Thus, we introduce the following quantities as indices that show the uniformities of average velocity and turbulence intensity.

$$E_U = \frac{1}{2hU_m}\int_{-h}^{h}\left|U - U_m\right|dy \tag{1}$$

$$E_{rms} = \frac{1}{2hu_{rms,m}}\int_{-h}^{h}\left|u_{rms} - u_{rms,m}\right|dy \tag{2}$$

Here, h (x) is the distance from the x-axis to the channel wall and $u_{rms,m}$ indicates the cross-sectional average of u_{rms}. The smaller E_U and E_{rms} are, the higher the uniformity degree is.

The results for the smoothly convergent channel are shown in Fig. 8. The uniformity of the average velocity distribution is high for the tapered and wavy shapes. Furthermore, it is confirmed that the tapered shape shows efficiency in terms of turbulence intensity.

IV. Conclusions

Visualization experiments using a smoke wire method and hot-wire velocity measurement were performed for a flow in a modeled headbox of a papermaking machine. The effects of the converging channel on the wake behind the plate, where a turbulent boundary layer is formed, were investigated. The principal achievements and results of this study are summarized as follows.

(1) A method of controlling the wake behind the partition plate was developed by adjusting the configurations of the channel and trailing edges, and a scheme for the improvement of the channel in the headbox was obtained.
(2) Rectifying through a converging channel is effective in making the distributions of average velocity uniform and in reducing turbulence intensity. However, for the rectangular shape, the converging effect is reduced by half since the vortex separated at the trailing edge grows up to a periodic Karman's vortex street, and a rather strong turbulence is produced.
(3) For the partition plate inserted into the dispersion part of the headbox, it is preferable for the trailing edge to have a tapered configuration. Furthermore, it is advisable to use simultaneously convergent channels as well.
(4) Upon applying the results of this study to an actual papermaking machine, a trailing edge with a wavy shape is expected because it is absolutely necessary to further improve the dispersion of pulp fibers.

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