A Principle of Producing Multi-ply Paper Using a Wire in an Inclined Wire Machine

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Abstract: In this study, we improved the dispersibility of the stocks in the headbox of an inclined wire machine to produce a distinct paper, and analyzed some factors affecting paper formation in the production of multi-ply paper. We used FLUENT6.3 to analyze the flow of the stocks in the headbox and select the structure of the diffusion part required for improving the dispersibility of fibers. Moreover, based on a simulation experiment, the optimal rational angle of the diffusion part (γ) was found to be approximately 8°~10°, and it improved the paper formation in the case of usage of two plates. Using the equation for the formation of paper layers in the headbox of an inclined wire machine, we obtained a paper with the given basic weight by controlling the inclined angle of the wire (α), initial height of water (H), and concentration of the stocks. We considered the effect of α and H of the stocks in the headbox on the fiber distribution, and according to the results, α should be set as approximately 20°~30° and H should be maximally high. When producing multi-ply paper by a wire, the line pressure of the couch roll should be maintained at 1.8~2.0 kN/m to avoid the damage to the paper sheets. In addition, we found the optimal structure parameter of the dehydrated roll was as follows: hole ratio of approximately 30% of the dehydrated roll surface area, width of 1.5~2.0 mm, slot pitch of 5~6 mm, slot depth of 2~3 mm, and inclined angle of diffusion part (β) of 5°.

Keywords: inclined wire machine; headbox; fiber suspensions fluid; multi-ply paper; papermaking

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1 Introduction

A paper machine, as an equipment for producing paper, can be classified into two types, namely, cylinder mold and Fourdrinier type, and in newspaper production, the double wire type is widely used[1].

The inclined wire type is a transformative type of a Fourdrinier paper machine,

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and its drainage combines the principles of both the cylinder mold and Fourdrinier type.

A primitive inclined wire machine was developed in the 1930s to produce a distinct paper using long fibers, and the wire of this type is very similar to the wire of a Fourdrinier machine[2-3].

An inclined wire machine is not suitable for producing ordinary paper because it is an equipment for manufacturing a distinct paper without long fibers which have poor properties in the papermaking process at a very low pulp concentration (0.01%~0.05%). An inclined wire machine operates at a low pulp concentration, and therefore, it needs a large amount of water during the papermaking process.

We chose a rational structure for the headbox that was suitable for the properties of 50″- and 100″-paper machines to produce various types of distinct and functional papers, and we developed the principle for papermaking by using an inclined wire machine.

2 Analysis of fluid flow in headbox of inclined wire machine and choice of its rational structure

2.1 Mathematical modeling for flow of stocks in inclined wire headbox

There have been significant developments in the study of structure of the headbox to improve the dispersibility of fibers. For example, a control system for the dilution factor and basic weight of the paper in its section was realized[4], and the fiber distribution (formation) was improved by developing a new vibration system by the calculation and design of a high-speed machine[5].

We analyzed the flow property of the stocks by using FLUENT6.3 in the headbox of an inclined wire machine, which is used for producing a distinct paper.

Modeling the flow field of a fluid mathematically, we obtained the following equations[6].

Mass conservation:

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x_i}(\rho U_i)=0 \tag{1}$$

Where ρ and U=(U_1,U_2,U_3) are the density and velocity of the fluid in time t and at position x=(x_1, x_2, x_3), respectively.

Momentum conservation:

$$\frac{\partial}{\partial t}(\rho U_i)+\rho U_j\frac{\partial U_j}{\partial x_j}=-\frac{\partial p}{\partial x_i}+\frac{\partial}{\partial x_j}(\mu\frac{\partial U_i}{\partial x_j}-\rho\overline{u_i'u_j'}) \tag{2}$$

Where p is the pressure and μ>0 is the viscosity coefficient.

Turbulence model: this yields the equation for determining turbulence viscosity coefficient μ_t. Various models are used for its calculation, and here we use the standard k-ε model[7].

$$\frac{\mathrm{d}}{\mathrm{d}t}(\rho k)=\frac{\partial}{\partial x_j}[(\mu+\frac{\mu_t}{\sigma_k})\frac{\partial k}{\partial x_j}]+G_k-\rho\varepsilon, \tag{3}$$

$$\frac{\mathrm{d}}{\mathrm{d}t}(\rho \varepsilon)=\frac{\partial}{\partial x_j}[(\mu+\frac{\mu_t}{\sigma_\varepsilon})\frac{\partial \varepsilon}{\partial x_j}]+C_{\varepsilon 1}\frac{\varepsilon}{k}G_k-\rho C_{\varepsilon 2}\frac{\varepsilon^2}{k}, \tag{4}$$

Where k is the turbulence kinetic energy, ε is its rate of dissipation, σ_k and σ_ε are the turbulence Prandtl numbers for k and ε, respectively, G_k is the generated turbulence kinetic energy due to the mean velocity gradient, and $G_{1\varepsilon}$, $G_{2\varepsilon}$ are the given constants.

Turbulence viscosity coefficient μ_t is computed by combining k and ε as follows:

$$\mu_t=\rho C_\mu\frac{\varepsilon^2}{k}$$

Where C_μ is a constant.

Based on the flow models (1)~(4) defined in Equations (1)~(4), we analyzed the property of the paper stock flow in the headbox of an inclined wire machine.

2.2 Flow property of stocks and selection of structure of diffusion part

We allow the flow of the headbox in the width direction to smooth and unify the suspension of the pulp fibers that enter the bath of the headbox using the diffusion part to ensure a flat flow of the paper stock with a simple structure. Fig.1 shows the structure of the diffusion part.

As shown in Fig.1, width B of the diffusion part has to be equal to width b of the bath of headbox, and it is selected based on the size of the machine.

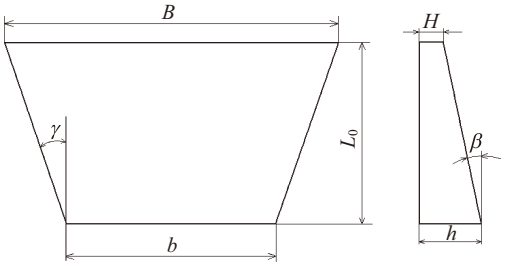


Fig.1 Structure of diffusion part

Height H and inclined angle β of the diffusion part entering the bath of the headbox are determined by the condition that the entrance of the diffusion part is not larger than the cross-section of the entrance connected to the supplying pipe of raw materials. This implies that it must satisfy $B \cdot H \leqslant b \cdot h$.

If the cross-section of the entrance of the diffusion part entering the bath of the headbox is larger than the one connected to the supplying pipe of the raw materials, then the air will be mixed in the stocks, air drops in the bath will rise, and bubbles will be formed, which is not good in the flow and deckle of the stocks. Moreover, the stocks entering from the pipe supplying raw materials are distributed along the width direction of the machine and the flow rate decreases; consequently, the fibers in the stocks become entangled.

To analyze the flow property of the stocks, we assume that the stocks enter the entrance of the diffusion part at a rate of 10 m/s along the width direction of the headbox.

Fig.2~Fig.4 display the results of the analysis of the flow property of the stocks.

According to the results of the simulation with FLUENT6.3, the rational diffusion angle (γ) is approximately 8°~10°.

If we set γ as 10°, then length L of the diffusion part from the supplying pipe of raw materials to the entrance of the bath of the headbox will increase. Therefore, the size of the machine is larger, and consequently, the setting area of the wire parts in the process for producing the paper is larger.

To overcome this issue, the entrance part of the supplying pipe of the raw materials may be made into a circular cone. Then, combining it with the entrance of the diffusion part, we can decrease L.

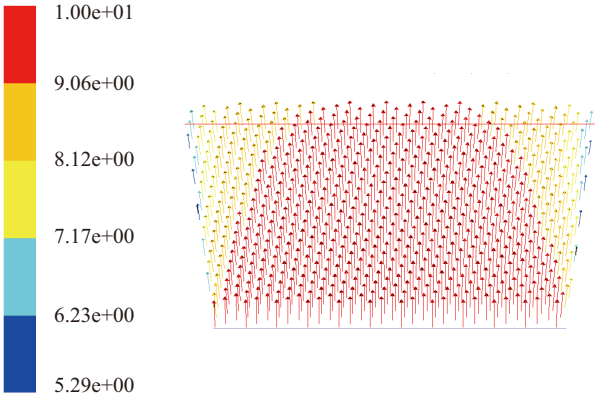


Fig.2 Flow property of paper stocks at γ = 8°

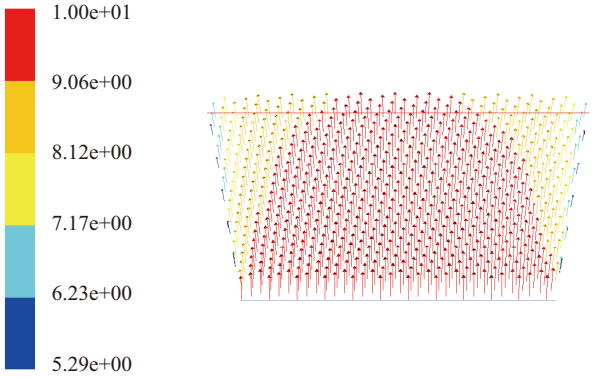


Fig.3 Flow property of paper stocks at γ = 10°

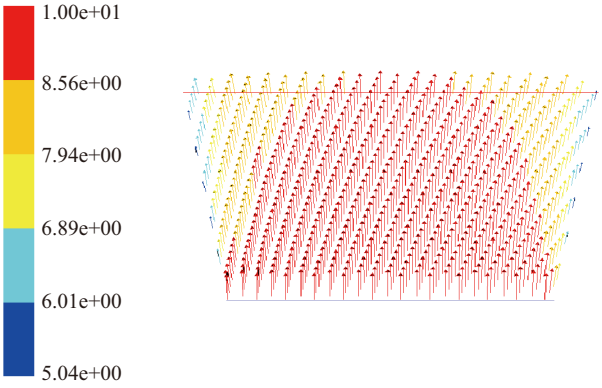


Fig.4 Flow property of paper stocks at γ = 12°

2.3 Flow property of stocks in bath of headbox

The stocks are distributed uniformly along the width direction of the machine by the diffusion part entering the bath of the headbox. Subsequently, the stocks keep an equilibrium on the flow through plate, and then are dehydrated through the wire, and a sheet is formed.

We analyze the flow property of the stocks based

on the diffusion part in the bath of the inclined wire headbox by using FLUENT6.3. Then, we assume that the flow of the stocks through the diffusion part is uniform along the width direction at a rate of 5 m/s.

Fig.5~Fig.7 show the distribution of the flow velocity of the stocks in the bath of the inclined wire headbox.

As shown in Fig.5, without a plate in the bath of the headbox, the stocks enter through the entrance without a decrease in the flow rate. Consequently, the flow rate of the stocks is higher than the wire rate. Therefore, in the paper formation, damage occurs in the region of the paper sheets, the fibers of stocks in the bath are not distributed sufficiently in all the directions, and the difference of strength in the across-vertical direction of the paper increases. Moreover, after the stocks leave the entrance of the bath, a rotation occurs, which has a negative effect on the paper sheet formation.

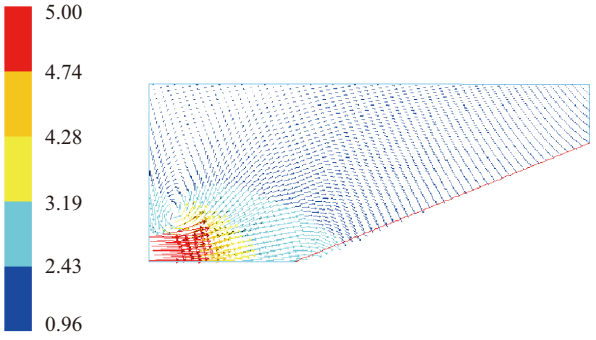


Fig.5 Flow property of paper stocks without plate

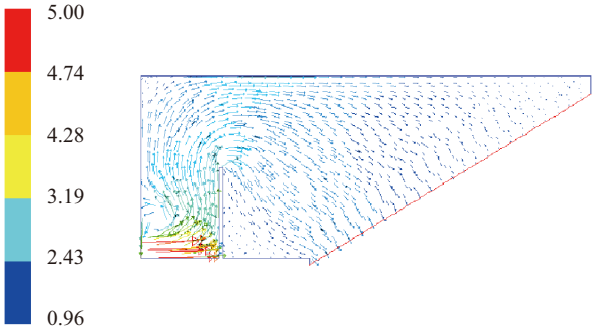


Fig.6 Flow property of paper stocks with one plate

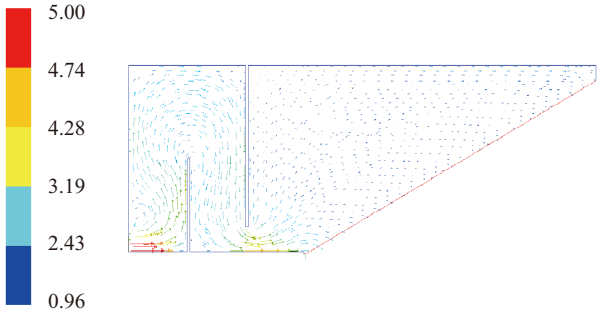


Fig.7 Flow property of paper stocks with two plates

The case of one plate in the bath of the headbox (Fig.6) provides a better condition for forming paper sheets than the case without a plate. Because here, the stocks enter through the entrance of the bath, there is a decrease in the flow rate. In comparison, after passing the plate, there is a small rotation, which might slightly affect the paper sheet formation.

In the case of two plates (Fig.7), for the stocks entering the entrance of the bath, the flow rate becomes sufficiently stable, which helps the stocks form uniformly. The fibers of the stocks are sufficiently distributed in all the directions, and the difference of strength of across-vertical direction of the produced paper decreases.

3 Equation for formation of paper layers in inclined wire machine

The process for the formation of paper layers depends on filtering pressure P. Therefore, the basic equation for the formation of paper layers can be expressed as follows:

$$\frac{\mathrm{d}q}{\mathrm{d}t} = kc\frac{\Delta P(t)}{g(q_0+q)} \tag{5}$$

Where:

q—basic weight (kg/m^2),

q_0—wire coefficient (constant depending on the property of the wire, kg/m^2),

t—time for the formation of the paper layers (s),

ΔP—difference between the filtering pressures (Pa),

k—filtering coefficient (m/s),

c—concentration coefficient (kg/m^3),

g—gravitational acceleration (m/s^2).

In addition, concentration coefficient c may be represented as follows:

$$c = \frac{c_0 - c_w}{c_z - c_0}\cdot\frac{c_z}{T} \tag{6}$$

Where:

c_0—concentration of the paper stock,

c_w—concentration of white water,

c_z—concentration of the fiber layers on the wire,

T—ratio of the mass of goods on the raw material, where $c_0 \gg c_w$, $c_z \gg c_0$, and $T \approx 1$.

Therefore, we know $c \approx c_0$. This implies that concentration coefficient c is almost equal to the concentration of the stocks.

In Equation (5), ΔP is not a constant and it is a function of time t, i.e., $\Delta P(t)$.

The height of the pulp in the bath of the inclined wire decreases directly to the length (L) of the interval in the formation of the paper layers, and the difference between the filtering pressures varies linearly with it.

Setting the velocity of the wire as V and the length of the interval in the formation of the paper layers as L, we can express the difference between the filtering pressures as follows:

$$\Delta P(t) = \Delta P_0(1 - \frac{V}{L}t) \tag{7}$$

Where ΔP_0 is the difference between the filtering pressures initially.

Substituting Equation (7) into Equation (5) yields:

$$(q_0+q)\mathrm{d}q = kc\frac{\Delta P_0}{g}(1-\frac{V}{L}t)\mathrm{d}t \tag{8}$$

Integrating the above by using the boundary condition (q is (0, q), t is (0, τ)), we have:

$$q = \sqrt{kc\frac{\Delta P_0}{g}(2\tau - \frac{V}{L}\tau^2) + q_0^2} - q_0 \tag{9}$$

Where τ is the time when the formation of the paper layers is completed.

Using $\tau = \frac{L}{V}$ and substituting it to Equation (9), we obtain:

$$q = \sqrt{kc\frac{\Delta P_0}{g}\cdot\frac{L}{V} + q_0^2} - q_0 \tag{10}$$

or

$$L = \frac{1}{kc}\cdot\frac{g}{\Delta P_0}(q^2 + 2qq_0)V \tag{11}$$

Equations (10) and (11) are the equations for the formation of the paper layers in the inclined wire machine.

Using the unit measures in the paper technology, Equations (10) and (11) are follows:

$$q = \sqrt{10kc\Delta H_0\cdot\frac{L}{V} + q_0^2} - q_0 \tag{12}$$

$$L = \frac{1}{10kc}\cdot\frac{q^2 + 2qq_0}{\Delta H_0}V \tag{13}$$

Where:

the unit of q and q_0 is g/m^2,

the unit of c is %,

the unit of k is 10^{-6} m/s,

the unit of ΔH_0 is m.

Using Equations (12) and (13), we can calculate the length of the interval in the formation of paper layers needed to obtain a paper of a given basic weight under the given conditions (the rate of the wire, concentration of the stocks, and initial filtering height of water).

In contrast, setting the angle of the inclined wire as α, we have:

$$\sin\alpha = \frac{\Delta H_0}{L} \tag{14}$$

Substituting Equation (14) into Equations (12) and (13) yields:

$$q = \sqrt{10kc\frac{\Delta H_0^{\ 2}}{V\sin\alpha} + q_0^2} - q_0 \tag{15}$$

$$\sin\alpha = 10kc\cdot\frac{\Delta H_0^2}{(q^2 + 2qq_0)V} \tag{16}$$

Using Equations (12) and (13), we can obtain a paper with a given basic weight by controlling the angle of the inclined wire, rate of the wire, initial height of water, and concentration of the stocks.

In addition, we can calculate the angle of the inclined wire suitable for producing the paper with operation of the machine and of a given basic weight.

In contrast, as we know from the above equations, we must increase the concentration of the stocks to reduce the waste of water and further increase the productivity of the paper machine.

However, there exists a limitation in increasing the concentration of the stocks to maintain the quality of the production. Therefore, we must determine the appropriate concentration of the stocks to improve the

quality of the production and reduce the waste of water. Moreover, we must design the rational elements of the wire parts and decide the operational conditions.

4 Principle for producing multi–ply paper by one wire

The principle for producing multi-ply paper using one wire in an inclined wire machine is demonstrated here.

The stocks completed in the composite process are rectified by passing the diffusion part and plate through the headbox with a controlled concentration.

In a paper machine, we can set 1~3 headboxes and we can adjust the numbers of headboxes according to the requirement. We can place stocks having the same or different properties in each headbox. When we place stocks having the same property in several headboxes, we can manufacture a thick paper with a more basic weight. Conversely, when we place different stocks in the headboxes, we can obtain multi-ply paper having different properties.

The basic weight of the paper in each layer is 50~80 g/m^2.

If we want to manufacture a two-layer paper using the machine, then we add the sheets formed in two headboxes, and similarly, a three-layer paper is manufactured by adding the sheets formed in three headboxes. This implies that to manufacture an *N*-layer paper, *N* headboxes must be set up. The size of a headbox is approximately 1600~1800 mm.

4.1 Effect of inclined angle of headbox on paper sheet formation

In our experimentation, we used non-bleaching sulphate pulp (NUKP) and mixed-waste paper pulp as the materials of the stocks. The experiment was performed under the following conditions: extracting condition 36″, beating degree 42°SR, extracting concentration 0.2%, maximal height of water 200 mm, and extracting rate of 15 m/min. Varying the inclined angle of the headbox as 10°, 20°, 30°, and 40°, we measure the directivity of the fibers and thickness uniformity of the stocks.

The directivity of the fibers in the extracting papers can be determined by the naked eye and difference of breaking length (BL) between MD and CD of the paper is shown in Table 1.

The method for measuring the thickness is as follows: we first cut a piece of paper with length of 50 cm from the extracting paper and make pieces in size of 10 cm×10 cm. We then measure the thickness of each piece approximately 5~10 times, and denote its average as $\overline{X_D}$. The instrument for measuring the thickness is a caliper (ZHD-4) with a diameter of 16 mm.

The thickness uniformity of the paper is calculated by the following equation:

$$D_f = \frac{\sigma_D}{\overline{X_D}} = \frac{\sqrt{\sum_{i=1}^{n}(X_{D_i} - \overline{X_D})^2 \frac{1}{n}}}{\overline{X_D}} \times 100\% \quad (17)$$

Where:

D_f—thickness uniformity of the paper, %,

σ_D—dispersion of the measured value, mm,

X_{Di}—thickness measurement value of each piece, mm,

$\overline{X_D}$—average of the thickness measurement values, mm,

n—measurement number,

The experimental results are presented in Table 1.

Table 1 Effect on paper sheet formation based on inclined angle of the headbox

Inclined angle of the headbox/(°)	Difference of BL between MD and CD/m	Formation /10^{-3} m
10	50	0.63
20	63	0.71
30	76	0.82
40	145	1.57

MD=machine direction; CD=cross direction; BL=breaking length.

Table 1 shows that the difference of BL between MD and CD of the paper gradually increases as the inclined angle of the headbox increases, and it rapidly increases when the inclined angle of the headbox is larger than 30°. The reason is that as the inclined angle increases, a stopping phenomenon occurs for the stocks in the headbox bath, and so, paper layers are formed owing to the fibers being dragged in the movement

direction of the wire.

Furthermore, the thickness uniformity in the extracting paper gradually deteriorates as the inclined angle increases. As it is larger than 30°, there is a rapid deteriorated trend. This implies that as the inclined angle of the headbox increases, the fibers of the stocks in the headbox bath are not distributed uniformly and are intertwined; hence, the formation of paper deteriorates.

In contrast, in the case that the inclined angle of the headbox is small, it is good for the formation of paper sheets. However, in this scenario, the water height of the stocks must be kept constant when extracting the paper in the headbox. This enlarges the installation area of the wire part because the length in the formation of the paper sheet is longer. Therefore, the angle of the inclined wire headbox in the production of multi-ply paper must be selected rationally to reduce the setting area of the wire parts in accordance with the qualitative index of the paper and properties of medium- and small-sized plants. Moreover, we believe that it may be rational to select the setting inclined angle of the headbox between 20° and 30°.

4.2 Effect of water height of stocks in headbox on paper formation

In our experiment, we used mixed-waste paper pulp with a beating degree of 42°SR as the material of the stocks. We analyzed the effect on the formation of paper sheets by varying the water height of the stocks in the headbox. This was done when extracting papers of 80 g/m^2 under the condition of paper stock concentration of 0.3% and inclined angle of the headbox of 25°.

The experimental results are exhibited in Fig.8. Fig.8 shows that we can increase the maximal height of the water of the stocks by controlling the dewatering quantity in the interval in which the paper sheet is formed when extracting the papers from the inclined wire headbox. Consequently, the difference of BL between MD and CD of papers is reduced and paper formation is improved. Increasing the water height of the stocks in the headbox is advantageous to the

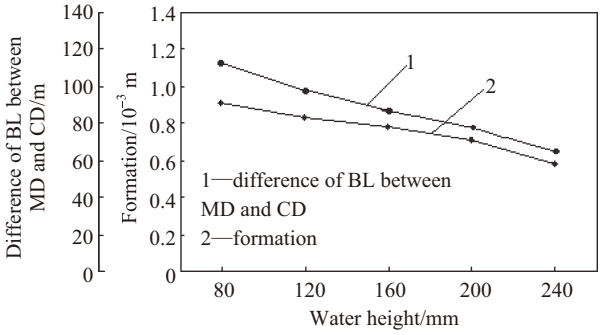


Fig.8 Effect on formation according to water height

formation of paper sheets because with increasing water height, the fibers in the stocks become smoothly distributed in all directions. Therefore, we must raise the water height of stocks as much as possible when extracting papers in the inclined wire headbox.

4.3 Determination of optimal line pressure in couch roll

A large increase in the line pressure in a couch roll corresponds to a dry paper sheet and significant quantity of water exhausting from it. Finally, the dehydration in the dehydrating roll becomes abnormal and the paper is destroyed. Oppositely, a small line pressure in a couch roll implies a small quantity of water exhausting from the stocks. Moreover, even though the dehydration in the dehydrating roll is normal, there occurs a phenomenon in which the paper sheets are separated from the blanket owing to the low drying level of the wetting stocks after passing the couch roll.

To determine the optimal line pressure of the couch roll, we used mixed-waste paper pulp as the material and performed the experiment under the following conditions: inclined angle of the headbox of 25°, concentration of the stocks of 0.3%, beating degree of 42°SR, extracting rate of 15 m/min, and basic weight of 80 g/m^2.

We set up a vacuum absorption box in the wire part and measure the dryness of the paper sheets and thickness uniformity of the wetting paper sheets formed in the headbox before and after passing through the couch roll. The pressure in the vacuum absorption box is 12.5 kPa.

Table 2 shows that if the line pressure of the couch

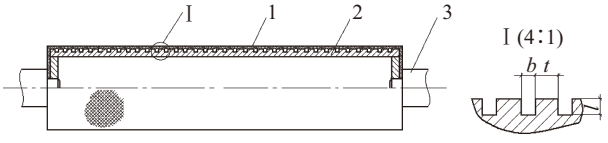
roll is higher than 1.8 kN/m, then the dewatering quantity from the wet sheet increases and water through the dewatering roll is not completely dewatered and it flows on the sheet. Consequently, the paper destruction phenomenon occurs when the line pressure is higher than 2.0 kN/m. Therefore, it is better to set the line pressure as 1.8~2.0 kN/m when producing multi-ply paper.

Table 2 Dewatering character of sheet according to line pressure of the couch roll

Line pressure/(kN · m^{-1})	Consistency of sheet/%
1.2	8.7
1.4	9.5
1.6	10.0
1.8	11.0
2.0	11.7
2.2	12.6

4.4 Structure of dewatering roll and determination of inclined angle (α) of wire

Fig.9 shows the structure of new dewatering roll. The distinct feature of the new dewatering roll is different from that of the previous one in that it is not covered with a rubber layer on the surface of the roll, which is instead made of steel or cast iron. We bore a screw hole in it and placed a resinous net on it.



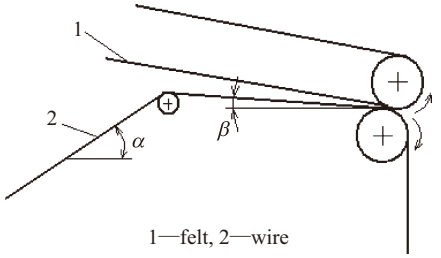
1—wire, 2—roll, 3—shaft

Fig.9 Structure of new dewatering roll

The screw hole is bored to spread out in both sides, starting from the center of the roll.

Based on the experiment, the most rational ratio of the holes is approximately 30% on the surface area of the roll, width of the screw hole is 1.5~2.0 mm, and its pitch is 5~6 mm. The depth is determined by the wall width of the main roll body, and in general, it is 2~3 mm.

As shown in Fig.10, the wetting paper sheets formed on the wire change the direction by the guidance roll and enter the space between the dehydrating roll and couch roll.



1—felt, 2—wire

Fig.10 Position of dewatering roll

If the wire entered horizontally or with an upper incline in the space between the dehydrating roll and couch roll, then the exhausted water under the pressing force flows onto the paper sheets formed on the wire, thereby destroying the paper sheets. Therefore, the wire must enter with a low incline in the space between the dehydrating roll and couch roll.

In addition, a large β is also unreasonable in the installation of the headboxes and dewatering rolls; therefore, we must determine the rational β. To this end, we measure the length (L_w) of the water overflowing the wire when the paper sheets are compressed and exhausted in the dewatering roll, changing β.

We use NUKP and mixed-waste paper pulp with a beating degree of 42°SR. The experiment was conducted under the following conditions: inclined angle of the headbox of 25°, concentration of the stocks of 0.3%, extracting rate of 15 m/min, and basic weight of 80 g/m^2.

We present the results in Table 3.

According to Table 3, water does not overflow from the couch roll to reach the wire and that the paper sheet formation is not destructed when the inclined angles of the headbox are 4° and 5° for the NUKP and mixed-waste paper pulp, respectively. Therefore, for the rational installation of the dehydrating roll to produce multi-ply paper, it is better to set the entering inclined angle as 5°.

Table 3 Effect of the inclined angle in dewatering roll

Inclined angle/(°)	1	2	3	4	5
L_w/mm	67	34	13	7	0

As mentioned above, we developed the principle for producing multi-ply paper by using a wire in an inclined wire machine and practiced it. It was found that the structure of the machine was simple.

5 Conclusion

In this study, we chose the structure of the headbox in which we could obtain a paper product with an ideal fiber distribution using an inclined wire machine. Moreover, we demonstrated the principle for producing multi-ply paper using a wire.

We analyzed the flow properties of the stocks in the headbox of an inclined wire machine by using FLUENT6.3. According to the simulation, the rational angle of the diffusion part (γ) was approximately 8°~10°, and it was optimal to use two plates during the paper formation.

Using the equation for the formation of the paper layers in the headbox of an inclined wire machine, we could obtain a paper with a given basic weight by controlling the angle of the inclined wire, initial height of the water, and concentration of the stocks.

We explored the effect of the inclined angle of the wire part and the water height of the stocks in the headbox on the fiber distribution. It was concluded that the rational inclined angle of the wire (α) was approximately 20°~30° and water height (H) could be set maximally high.

For the production of multi-ply paper by a wire, the line pressure of the couch roll should be maintained within 1.8~2.0 kN/m, which would not cause damage during the paper formation in the sheet region.

We found the optimum structure parameters for the dehydrated roll were as follows: hole ratio in the dehydrated roll of approximately 30% of the roll surface area, width of 1.5~2.0 mm, slot pitch of 5~6 mm, slot depth of 2~3 mm, and inclined angle of diffusion part (β) of 5°.

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