Send Orders for Reprints to reprints@benthamscience.ae

Open Access

Flow Characteristic of Hydraulic Headbox Based on Complementary Pulp Distribution

Liu Wei and Ji Xiaohui*

College of Mechanical and Electrical Engineering, Guangdong University of Petrochemical Technology, Maoming, Guangdong, 525000, P. R. China

Abstract: In order to study the effect of complementary pulp distribution, computational fluid dynamic (CFD) was used to research on flow characteristic of hydraulic headbox based on complementary pulp distribution. Mass flow rate out of mixing chamber and velocity distribution at slice of headbox were experimented. The results show that because of simplified design, there was a little gradient of velocity and pressure which caused non uniform distribution of mass flow rate out of branch pipes. Distribution of mass flow rate was ascended from inlet of header to outlet and the deviation was -2.33% and 1.82%. There was intense interference between the jets of branch pipes in mixing chamber and the jets could be sufficiently and complementarily mixed in rows and ranks. But the interference in the jets caused the accumulation of the jets in the central section of mixing chamber and mass flow rate out of mixing chamber in the center was higher than the two sides, and the maximum deviation was 0.538%. Distribution of velocity of pulp stock at slice of headbox was very gentle and curve of distribution presented only slight fluctuation. The maximum deviation of velocity was only 0.175%. From the results of the experiment, the test values of mass flow rate out of mixing chamber were inosculated with the calculated values and tested values of velocity at the slice of headbox were in accordance with the calculated values. The results of experiment explained that the method of complementary pulp distribution was reasonable and could obviously improve performance of pulp distribution of hydraulic headbox.

Keywords: Complementary pulp distribution, computational fluid dynamic, flow, hydraulic headbox, numerical simulation.

1. INTRODUCTION

The hydraulic headbox is the heart of the modern high-speed papermaking machine, joining the pulp feeding part and paper forming part. The main purpose is to convert the flow of pulp in a round pipe into a uniform flat jet several meters wide that will fall on the wire to start the dewatering process.

In the development of a headbox, though there are open headbox, air-cushioned headbox, hydraulic headbox and high-consistency headbox successively, the hydraulic headbox is applied widely [1]. In order to ensure the paper forming quality, the dilution water system had been introduced into the headbox, namely the dilution water headbox [2, 3]. To keep up with uniform pulp distribution, many pulp distributors, such as extended channel type, multiple halving type, multiple branches type and cross flow type, were used in headbox, but they were fallen into disuse [4, 5]. The rectangularly tapered distributor became more and more important in the end of the twentieth Century. Pulp enters tapered pipe from inlet and is distributed through branches on the tapered pipe. According to fluid mechanics, the same pressure in tapered pipe causes backwall shape of rectangularly tapered pipe which is very complicated [6]. So there is obvious longitudinal pressure difference in the linear simplified tapered pipe and the piecewise approximation tapered pipe which are widely used in the papermaking machine. Furthermore, the higher the speed, the more obvious the pressure difference [7, 8]. The circular distribution for headbox could realize the pulp flow at uniform pressure and effectively solve the problem of pressure difference, but central distribution causes the difficulty for the breadth of papermaking machine to meet the increasing need [9]. Recently, a new pulp distribution which makes use of the pressure difference to assure uniform pulp distribution was reported and named as complementary pulp distribution [10].

The headbox has always been a hot topic for many researchers. Some researchers tried to study the ways of improving pulp distribution and design method of pulp distributor from the view of structure optimization of the headbox [11, 12]. In order to avoid fibre flocculation, the stock flows out of mixing chamber of headbox to keep it turbulent. So structure design of the turbulence generator is very important [13-17]. Design of headbox is greatly influenced by flow characteristic of headbox, so people commonly adopt method of numerical simulation to study the headbox due to its complicated structure [8, 18].

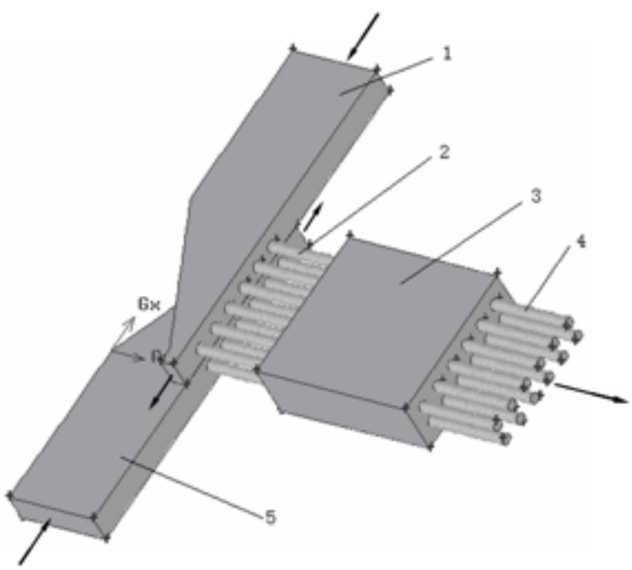
In the following section, the complementary pulp distribution is discussed briefly. In Section 3, computational fluid dynamic (CFD) is adopted to study the flow characteristic of headbox based on complementary pulp distribution. In Section 4, pulp distribution of mass flow rate out of mixing chamber and velocity distribution at slice of headbox are experimentally discussed, and in the concluding section, the important findings are reiterated.

*Address correspondence to this author at the College of Mechanical and Electrical Engineering, Guangdong University of Petrochemical Technology, Maoming, Liaoning, 525000, P.R. China; Tel: +86 668 2923531; E-mail: lwjxh2002@163.com

1874-155X/15 2015 Bentham Open

2. COMPLEMENTARY PULP DISTRIBUTION

Nowadays, the rectangularly tapered distributor where the pulp stock enters from inlet of pipe, is applied widely on the papermaking machine. But distribution of the mass flow rate out of branch pipes and onto the pipe is not uniform because of structure of the distributor and the non-uniformity, obviously increasing with an increase in the tapered header length [19]. If the rectangularly tapered header is divided into two rectangularly tapered headers which have absolutely same structure, mass flow rate and reflux ratio, two rectangularly tapered headers have identical flow characteristic and the same distribution of mass flow rate out of branch pipes. A rectangularly tapered header is kept on the other, keeping it symmetrically stacked together. Pulp stock symmetrically enters the two tapered headers from big ends and flow towards each other and flow out of the pipes from small ends as shown in Fig. (**1**). So, distribution curve of pulp mass flow rate out of branches of two rectangular tapered headers is just opposite. The pulp stock from branch pipes of two tapered headers enters the mixing chamber and is mixed. The mixture in the mixing chamber is average mixture of pulp whose distribution curves are just inverted in view of a row of branch pipes. To the corresponding branch pipes in a rank, the mixture is complementary and is average mixture between large mass flow rate and small mass flow rate. So, distribution of mass flow rate at outlet of mixing chamber is uniform and meets request of uniform pulp distribution. This is complementary pulp distribution [10].



1. Distributor (Upper) 2. Manifold Tubes 3. Mixed Chamber 4. Turbulence Generator 5. Distributor (Lower).

Fig. (1). Complementary pulp distribution.

3. NUMERICAL ANALYSIS ON FLOW CHARACTERISTIC OF HEADBOX

3.1. Physical Model

The headbox consists of two rectangularly tapered headers which are simplified, branch pipes, turbulence generator and steady chamber as shown in Fig. (**2**). The pulp stock from pulp pump is divided into two flows by tube line and enters rectangularly tapered header I and rectangular tapered header II respectively. The pulp stock is distributed along length of rectangularly tapered header by branch pipes and jet into mixing chamber with flow of different mass flow rate. In the mixing chamber, the violent interference between the jets causes pulp stock to complementarily mix into each other and distribute uniformly at outlet of mixing chamber. The stock out of mixing chamber flows into the turbulence generator to keep it turbulent. And then, the stock flows into the stable chamber, finally, on to the jets on the wire by slice of stable chamber.

3.2. Main Equations

This work of computational simulation mainly uses continuity equation, momentum equation and realizable k-ε model for turbulent flow. Main equations are as follows:

$$\frac{\partial \rho}{\partial t} + \rho \nabla \cdot \vec{V} = 0 \tag{1}$$

$$\begin{cases} \dfrac{\partial(\rho u)}{\partial t} + \nabla \cdot (\rho u \vec{V}) = -\dfrac{\partial p}{\partial x} + \dfrac{\partial \tau_{xx}}{\partial x} + \dfrac{\partial \tau_{yx}}{\partial y} + \dfrac{\partial \tau_{zx}}{\partial z} + \rho f_x \\ \dfrac{\partial(\rho v)}{\partial t} + \nabla \cdot (\rho v \vec{V}) = -\dfrac{\partial p}{\partial y} + \dfrac{\partial \tau_{xy}}{\partial x} + \dfrac{\partial \tau_{yy}}{\partial y} + \dfrac{\partial \tau_{zy}}{\partial z} + \rho f_y \\ \dfrac{\partial(\rho w)}{\partial t} + \nabla \cdot (\rho w \vec{V}) = -\dfrac{\partial p}{\partial z} + \dfrac{\partial \tau_{xz}}{\partial x} + \dfrac{\partial \tau_{yz}}{\partial y} + \dfrac{\partial \tau_{zz}}{\partial z} + \rho f_z \end{cases} \tag{2}$$

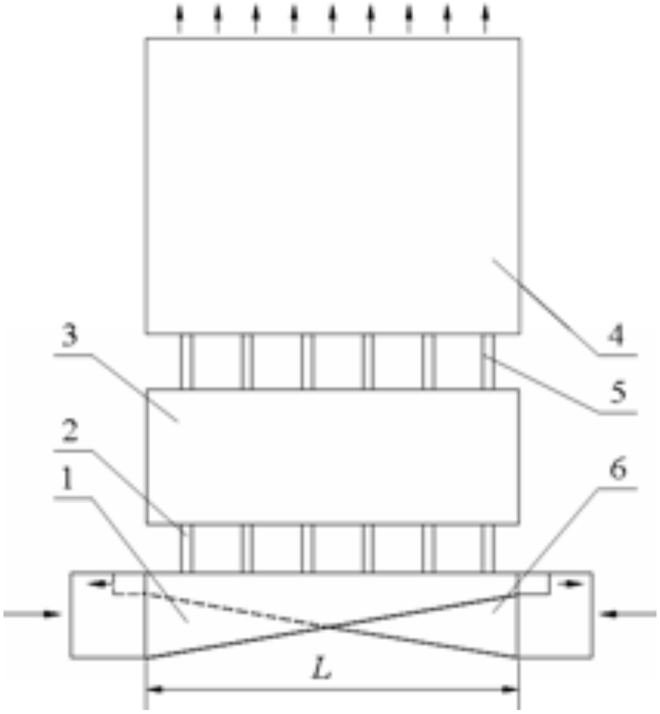
$$\rho \frac{dk}{dt} + \frac{\partial}{\partial x_i}\left(\rho k u_i\right) = \frac{\partial}{\partial x_i}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_i}\right] + G_k + G_b - \rho\varepsilon - Y_M + S_k \tag{3}$$

$$\rho \frac{d\varepsilon}{dt} + \frac{\partial}{\partial x_i}\left(\rho \varepsilon u_i\right) = \frac{\partial}{\partial x_i}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_i}\right] + \rho C_1 S \varepsilon - \rho C_2 \frac{\varepsilon^2}{k + \sqrt{\upsilon\varepsilon}} + C_{1\varepsilon}\frac{\varepsilon}{k} C_{3\varepsilon} G_b + S_\varepsilon \tag{4}$$

where the denotation of the variables in above equations has been explained in Reference [20].

3.3. Computational Model

In order to study complementary mixture of stock in mixing chamber and flow characteristic of headbox, the turbulent flow of stock was modeled with the Renolds-averaged Navier-Stokes equations applied for the headbox geometry. The solution uses a finite-volume, structured grid method with the realizable k-ε model for turbulent flow. The computational model is fully three-dimensional to represent all of the important flow features. To obtain high computation precision and reliable results, the branch pipes at inlet and outlet of mixing chamber were meshed by hexahedron, and the other meshed by tetrahedron. The SIMPLE method was adopted in coupling calculation of pressure and velocity.



1-Tapered Header i ; 2-Branch Pipes; 3-Mixing Chamber; 4-Stilling Chamber; 5-Turbulence Generator; 6-Tapered Header II.

Fig. (2). Physical model of headbox.

Commonly, consistency of the pulp stock from pump into headbox is 1%. The stock is turbulent and its flow characteristic is similar to water. The volumetric flow rate at the taper entrance was taken to be 150 m^3/h, which is a real value in laboratory. The recirculation rate was 10%.

3.4. Results and Discussion

3.4.1. Flow Characteristic in Rectangularly Tapered Pipe

The velocity distribution in two rectangularly tapered pipes is shown in Fig. (**3**). The velocity distribution is identical in two tapered headers because of identical structure and identical mass flow rate. From Fig. (**3**), it is known that there is obvious velocity gradient in two headers and the trend increases from inlet to outlet.

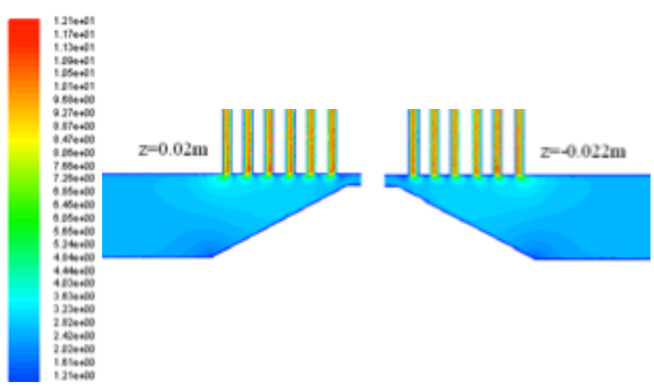


Fig. (3). Velocity contours in rectangular tapered header (m/s).

The pressure distribution in the tapered header is shown in Fig. (**4**). The pulp stock flows with the same pressure as expected, but according to Bernoulli Equation, the non-uniformity of velocity in tapered header inevitably causes the pressure distribution as not uniform. From width direction of the tapered header, the pressure gradually decreases and increases again near the outlet. The phenomenon does not accord with design of the tapered header and illuminate that simplified design method of tapered pipe is unreasonable.

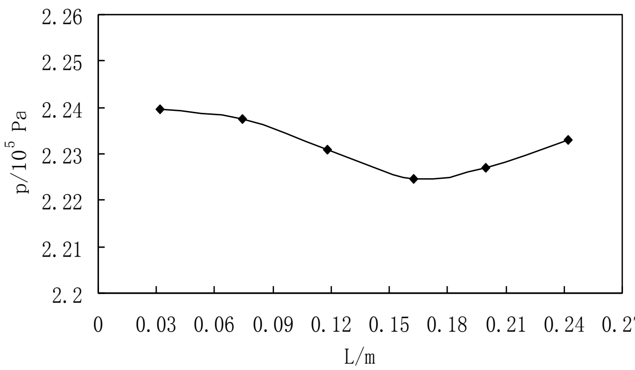


Fig. (4). Pressure distribution in rectangular tapered header.

The non-uniformity of velocity and pressure in tapered headers causes the mass flow rate out of branch pipes of tapered header obviously deviating from the expected value (the expected value is 2.9551 kg/s), as shown in Fig. (**5**). From inlet to outlet of tapered header, the mass flow rate out of branch pipes gradually increases, from the first branch pipe 2.8861 kg/s to the last branch pipe 3.0089 kg/s. The maximum deviation is near inlet, -2.33%, and near outlet, 1.82%. By comparing two curves in Fig. (**5**), it can be found that distribution of mass flow rate out of complementary header is similar to that out of tapered header.

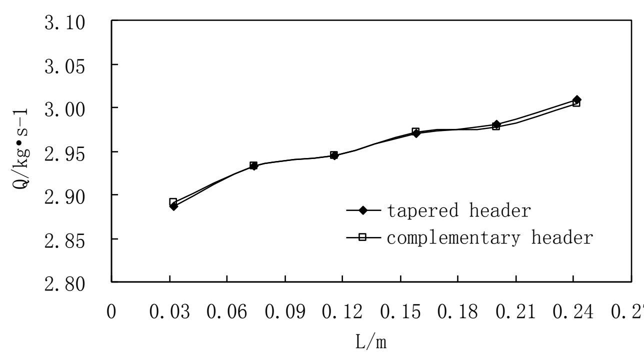
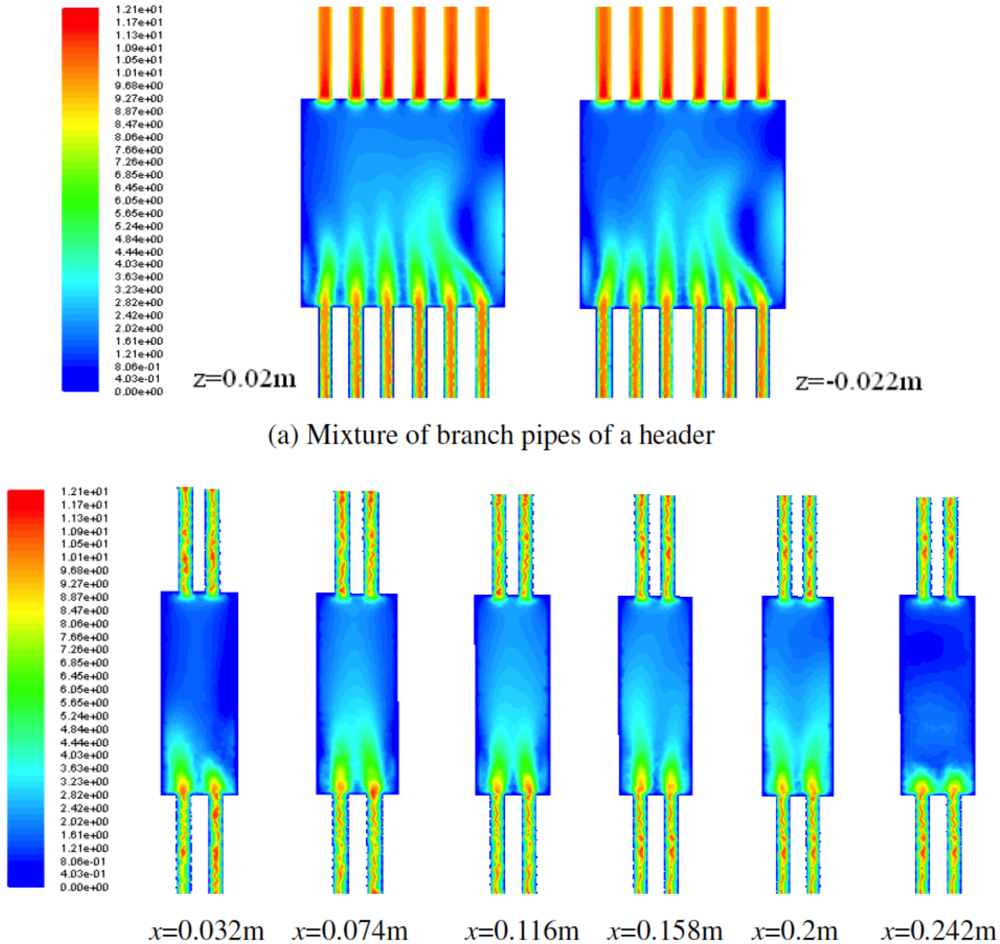


Fig. (5). Mass flow rate out of branch pipes.

3.4.2. Flow Characteristic in Mixing Chamber

The complementary pulp distribution makes use of non-uniformity of pulp distribution to gain uniform distribution of pulp by complementary mixture in mixing chamber, though the pressure and velocity have gradient in two rectangularly tapered headers and the mass flow rate out of branch pipes is not non uniform. The velocity distribution in mixing chamber is shown in Fig. (**6**). The mixing velocity distribution in branch pipes of each tapered header is shown in Fig. (**6a**). The violent entrainment and interference between branch pipes of each header are very beneficial for pulp average mixture. Because of different mass flow rates



(a) Mixture of branch pipes of a header

(b) Mixture of corresponding branch pipes between two headers

Fig. (6). Velocity contours in mixing chamber.

in branch pipes, the jet whose mass flow rate is larger produces much more entrainment and adjacent two jets are anear. The jet whose mass flow rate is largest engenders more deflexion. So the jets get together, and pulp stock mixed concentrates to middle of the mixing chamber. The mass flow rate out of mixing chamber in the centre is higher than the two sides at outlet of mixing chamber, which influences uniform distribution of pulp to some extent. The mixing velocity distribution in corresponding branch pipes of two tapered headers is shown in Fig. (**6b**). At x=0.032 m and x=0.242 m, the jets have strong deflexion and only mix inadequately because of intense interference of jets at other places. At other places, there is violent entrainment and interference between each corresponding branch pipe, so the pulp stock can rapidly mix and become integrated along the length of mixing chamber. In the mixing chamber, most of the jets of corresponding branch pipes can have fully complementary mixture, but do not reach the expected effect. So the structure of mixing chamber should be optimized to improve mixing effect of pulp stock.

The pulp stock flows out of mixing chamber into the turbulence generator after getting mixed in mixing chamber; the distribution of the mass flow rate out of turbulence generator is shown in Fig. (**7**). The maximum of mass flow rate in branch pipes after complementarily mixed is 2.971 kg/s, the maximum of deviation is 0.538%. While the maximum of mass flow rate in branch pipes not to be complementarily mixed is 2.979 kg/s, the maximum of deviation is up to 0.887%. From trend of distribution curve, the curve after complementarily mixing becomes gentler than not to be complementarily mixed and is closer to the expected line. It is illuminated that the complementary distribution can improve notably the performance of pulp distribution. As a result of the strong interference between jets in mixing chamber, the curve of distribution of mass flow rate shows that the middle part is higher than both sides. So the structure optimization of mixing chamber should be further investigated.

3.4.3. Velocity Distribution in Slice of Headbox

The pulp stock complementarily mixed enters the stable chamber which can eliminate defect of pulp stock as much as possible and make pulp flow uniform jet on wire. If velocity of pulp flow along width of slice is uniform, forming quality of paper will be good. The velocity distribution along width of slice of headbox is shown in Fig. (**8**). At both sides of the slice, the boundary layer of pulp flow near the wall could squeeze pulp flow to extrusion effect which causes smaller mass flow rate at both sides of slice. Whole velocity distribution curve of pulp flow is very gentle, with no sudden increase and decrease, near the expected line (v=14.26 m/s) as the broken line shown in Fig. (**8**), but with some fluctuation on the curve.

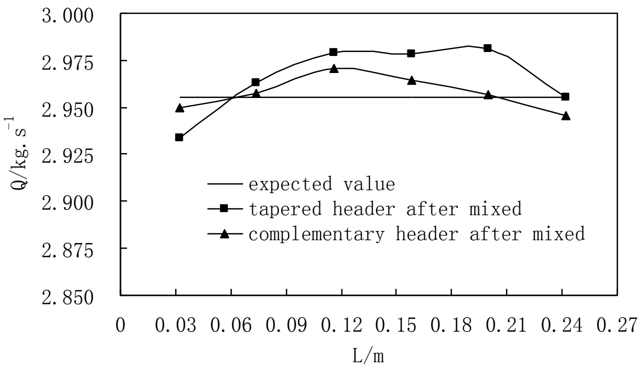


Fig. (7). Distribution of mass flow rate out of mixing chamber.

4. EXPERIMENTAL STUDY

4.1. Experimental Installation

The experimental installation and diagram are shown in Fig. (**9**). The pulp stock is pumped to the headbox and circumfluence part of pulp flow goes to pulp pool. The pulp through the slice of headbox gets into pulp tray and flows back into the pulp pool. In the experiment, the pulp distribution of mass flow rate out of mixing chamber and distribution of velocity at slice are tested. The mass flow rate is tested by TUF-2000H1 handheld ultrasonic flow meter whose sensor can measure the range of pipe diameter from 15 millimeters to 100 millimeters. The velocity is tested by Sensorline 7520 SVS laser velocimeter.

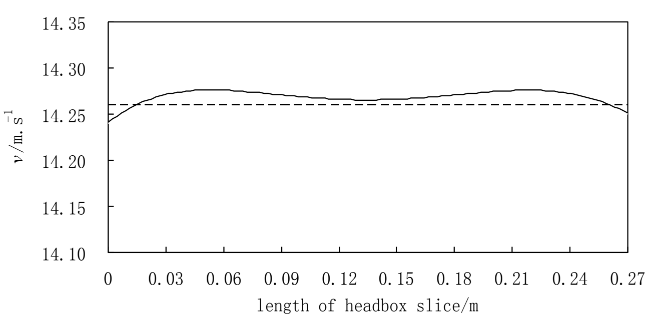


Fig. (8). Velocity distribution at slice of headbox.

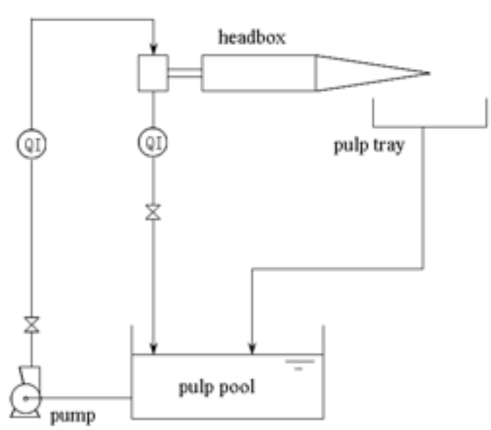


Fig. (9). Flow chart of experiment.

4.2. Results and Discussion

4.2.1. Distribution Performance at Outlet of Mixing Chamber

In the experiment, the mass flow rate of pulp out of mixing chamber is tested and compared to the calculated value as shown in Fig. (**10**). The tested values are in accordance with the calculated value of mass flow rate out of branch pipes of mixing chamber. Distribution performance of pulp complementary distribution is obviously better than that of former distribution. The mass flow rate at middle of the curve is a little larger than at both sides of curve because of interference between jets in mixing chamber, which is consistent with the analysis of part 3.4.2. The results show that the method of complementary distribution is very reasonable and can improve effectively the distribution performance of pulp. In order to further improve distribution performance, the structure optimization of mixing chamber is a good idea.

4.2.2. Distribution Performance at Slice of Headbox

Though the complementary distribution can obviously improve distribution performance at outlet of mixing chamber which is near the expected value, the effect of complementary distribution needs to be verified by velocity distribution of pulp out of slice of headbox. The velocity distribution at slice of headbox is tested in experiment at seven measuring points along the width of slice and is compared to the same points of slice of headbox adopting rectangularly tapered pipe distributor, as shown in Fig. (**11**).

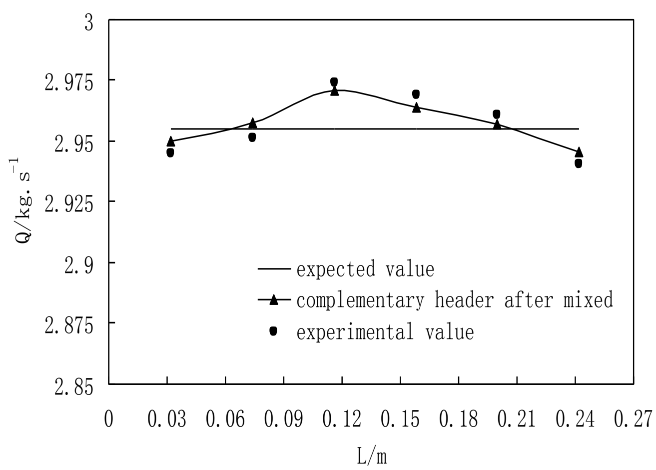


Fig. (10). Experimental values of mass flow rate out of mixing chamber.

Because unreasonable structure of rectangularly tapered pipe distributor causes non-uniformity of pressure and velocity, the velocity distribution of pulp flow at slice of headbox is also non uniform and fluctuates obviously. Curve of velocity distribution is notably deviated from expected curve where the velocity is 14.26 m/s which is shown as the broken line. The maximum of velocity is 14.34 m/s, the maximum deviation 0.56%, the minimum velocity 14.2 m/s, and the maximum negative deviation -0.42%. After complementary distribution is adopted, distribution performance curve of pulp is improved remarkably with a slight fluctuation. The maximum velocity is only 14.28 m/s, the maximum deviation 0.14%, the minimum velocity 14.235 m/s, and the maximum of negative deviation -0.175%.

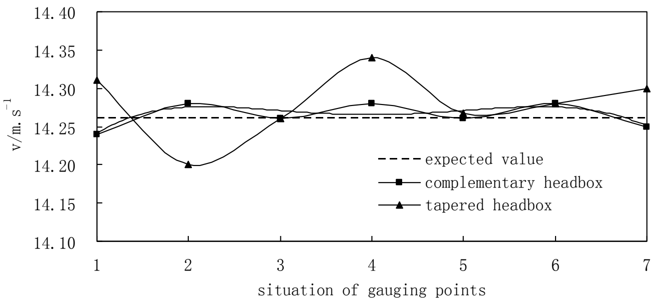


Fig. (11). Velocity distribution of slice of headbox.

CONCLUSION

The flow characteristic of hydraulic headbox with complementary distributor was numerically studied based on CFD. The pulp jets in mixing chamber can strongly mix and interfere with each other, and keep complementary mixing very well in rows and ranks. When pulp stock enters the stable chamber, whole velocity of pulp flow gradually becomes gentle. The velocity distribution at the slice of headbox is improved obviously, and curve of distribution is uniform near the expected curve. The experiment shows that tested values of mass flow rate are in good agreement with calculated values. Because of effectively complementary distribution of pulp in the mixing chamber, the uniformity of pulp distribution is transferred to flow in the stable chamber and can effectively improve quality of the pulp that flows to wire. The complementary distribution of pulp stock is reasonable and feasible.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

ACKNOWLEDGEMENTS

This work was financially supported by the Guangdong Province Science and Technology Plan Project (2012B03-1000019) and Guangdong Province University Innovation Project (631044).

REFERENCES

[1] M. C. Lin, “Design and development of headbox”, *World Pulp and Paper*, vol. 8, no. 4, pp. 39-44, 1989.

[2] M. D. Lloyd, “Stratified forming -a technology for the new millennium”, *Appita*, vol. 53, no. 3, pp. 188-194, 2000.

[3] L. Liu, and Y. T. Yue, “Application of dilution water distributior”, *Hei Lonhjiang Pulp and Paper*, vol. 5, no. 2, pp. 55-56, 2007.

[4] K. F. Chen, *Pulp and Papermaking Machinery and Equipment*, China Light Industry Press: Beijing, 2008, pp. 72-77.

[5] W. Liu, and K. F. Chen, “Research overview on distributor of headbox of high-speed paper machine”, *Paper & Paper Making*, vol. 30, no. 5, pp. 10-13, 2011.

[6] K. F. Chen, *Fluid Dynamic at Wet Section of the Paper Machine*, China Light Industry Press: Beijing, 1984, pp. 148-214.

[7] W. Liu, K. F. Chen, and Jun. Li, “Study of the fluid flow through the rectangular tapered tube distributor based on CFD”, In: *4th ISETPP. Research Progress in Paper Industry and Biorefinery*, Guangzhou, 2010, pp. 1260-1263.

[8] W. Liu, K. F. Chen, and Jun. Li, “Numerical simulation on the flow characteristic in rectangular tapered distributor”, *Journal of South China University of Technology*, vol. 39, no. 3, pp. 13-16. 2011.

[9] F. C. H. Yany, “New model distributor for headbox”, *World Pulp and Paper*, vol. 24, no. 3, pp. 46-48, 2005.

[10] W. Liu, and K. F. Chen, “Distributing mechanism and flow characteristic of a new pulp distributor”, *CIESC Journal*, vol. 63, no. 2, 2012, pp. 448-454.

[11] J. Hämäläinen, R. A. E. Mäkinen, and P. Tarvainen, “Optimal design of paper machine headboxes”, *International Journal of Numerical Methods in Fluids*, vol. 34, no. 5, pp. 685-700, 2000.

[12] X. Yang, K. F. Chen, and H. P. Wen, “Discussion on the working principle of inlet-header of headbox and its new calculation method”, *China Pulp & Paper*, vol. 28, no. 9, pp. 1-4, 2009.

[13] H. J. Youn, and H. L. Lee, “A numerical study of flow behaviour in the turbulence generator of headboxes”, *Appita Journal*, vol. 58, no. 3, pp. 196-201, 2005.

[14] Z. G. Yin, S. Q. Zhang, and Y. D. Huang, “Numerical simulation of serial sudden expansions pipe flow”, *Fluid Machinery*, vol. 33, no. 8, pp. 24-27, 2005.

[15] Q. Zhao, and D. R Pan, “Numerical simulation of ladder diffusion headbox”, *Xinan Pulp and Paper*, vol. 34, no. 4, pp. 15-18, 2005.

[16] Z. L. Xiao, and J. Yang, “Numerical simulation of inner flow field of the headbox nozzle and turbulent generator”, *Transations of China Pulp and Paper*, vol. 20, no. 1, pp. 185-189, 2005.

[17] J. Yang, Z. L. Xiao, and J. Y. Deng, “Optimal design method based on inner flow numerical simulation for mechanical structure of microturbulence generator”, *Chinese Journal of Mechanical Engineering*, vol. 43, no. 5, pp. 127-132, 2007.

[18] K. Pougatch, and M. Salcudean, “A computational study of the fluid flow through a hydraulic headbox”, *Tappi Journal*, vol. 4, no. 10, pp. 3-8, 2005.

[19] W. Liu, and K. F. Chen, “A Study of the influence on flow characteristic in the simplified rectangular tapered header under several design parameters”, *China Pulp & Paper Industry*, vol. 32, no. 6, pp. 17-20, 2011.

[20] W. Liu, “Flow characteristic of rectangularly tapered distributor based on the k-ε turbulence model”, *China Pulp & Paper Industry*, vol. 34, no. 8, pp. 30-33, 2013.

Received: December 23, 2014 Revised: February 2, 2015 Accepted: February 27, 2015

© Wei and Xiaohui; Licensee *Bentham Open*.

This is an open access article licensed under the terms of the Creative Commons Attribution Non-Commercial License (http://creativecommons.org/licenses/by-nc/4.0/) which permits unrestricted, non-commercial use, distribution and reproduction in any medium, provided the work is properly cited.