PIV Measurements of Flow immediately above Woven Fabrics

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ABSTRACT

Three-dimensional velocity fields in the single phase approach flow to a multiple layer woven forming fabric were measured using Particle Image Velocimetry (PIV). The measurements were conducted on a scale model of a forming fabric in a glycerin/water flow loop. Each strand on the paper side of the model forming fabric had a filament diameter of d=15 mm and the loop test section was 300 mm square, permitting the measurement of detailed velocity distributions over multiple strands of the fabric. The liquid viscosity and the flow speed in the loop test section were varied to achieve screen Reynolds numbers, Re_s, between 15 and 65. PIV measurements showed that the RMS variation of machine direction velocity is about 10% of the average Z direction velocity at a distance 0.25d above the fabric. The deviation of the Z direction velocity decreases from 15% at a plane 0.25d above the forming fabric surface to 4% at a plane 1.5d above the surface. The highest Z direction velocity is about 2.2 times of the lowest Z direction velocity at a plane 0.25d above the fabric. The Z direction velocity variation for a Reynolds number of 65 is 16% lower than that for a Reynolds number of 15. CFD simulations were done of the flow through the fabric using FLUENT^{TM} and those simulations were consistent with the PIV measurements within $\pm$ 9%.

INTRODUCTION

Paper making contains three basic processes: forming, pressing and drying. In the forming section, a dilute suspension of pulp in water, generally about 0.7% pulp by mass, is forced through a woven forming fabric to create a pulp mat. In this process, fibers are filtered from the suspension as the water flows through the fabric, Adanur [1]. The fibrous mat is subsequently pressed and dried to create paper.

It is known that the flow non-uniformity upstream forming fabric can have a profound effect on the printed end products, Danby [2] and Danby et al. [3]. To create a high quality, uniform density sheet of paper, it is important that the fiber mass distribution in the wet paper web is as uniform as possible, so a uniform velocity profile is desired on the upstream side of the fabric layer on which the mat is being formed.

The forming fabric structure is a complex three-dimensional woven matrix, which consists of machine direction (MD) and orthogonal cross machine direction (CMD) filaments in two or more layers. To make smooth paper, the filaments on the surface of the fabric in contact with the pulp are very fine (0.15mm in diameter, referred to as the "paper side"). To increase wear life and decrease running resistance, coarse filaments (0.3mm diameter on the "machine side") in contact with the papermachine are used, Johnson [4] and Johnson[5]. These characteristics can be seen in Fig.1.

To experimentally investigate the flow through forming fabrics, a scale model of a real forming fabric, originally designed by AstenJohnson, is manufactured by a Rapid Prototype Machine with the method mentioned by Vakil et al. [6] (Fig.2). The pulp at the beginning of the forming section has a very low concentration of fibers in water (0.7%), and therefore pure water was used in the experiments.

Research conducted by Dalpke et al. [7] shows that the Z-direction velocity of water through a forming fabric varies from 0.05 to 0.5 m/s depending on the impingement angle, position and headbox jet velocity, which implies a Reynolds number between 6.5 and 65 based on the paper-side filament diameter.

Due to the extreme complexity of the three dimensional structure of forming fabrics, previous research on the flow through forming fabrics greatly simplified the fabric geometry. Huang [8] and Huang et al. [9] did a numerical investigation of flow through banks of cylinders at low Reynolds number, smaller than 150, and found a downstream row of cylinders had little influence on an upstream row of cylinders provided that the surface separation between rows exceeded 0.7 times the upstream cylinder diameter ($Xs/d \geq 0.7$). Gilchrist et al. [10] measured the upstream velocity profile and pressure drop of the flow through two rows of cylinders. His experimental findings were consistent with the simulations of Huang. Green et al. [11] did filament-level three-dimensional simulations of the flow through single layer woven fabrics and found that uneven filament spacing produces only highly localized changes in the flow field. Vakil et al. [6] found a novel method to produce accurate CAD models of real forming fabrics. These CAD models were then input into a CFD code to predict the filament-scale flow through a forming fabric. The flow non-uniformity and its probable effect on paper were considered in that article.

The present work is a continuation of the aforementioned previous studies of forming fabrics. Here, we present results of Particle Image Velocimetry (PIV) measurements of the flow through woven fabrics. The organization of the article is as follows: the experimental methods are presented at the beginning. The following section presents and discusses the PIV results. Finally, there is a brief set of conclusions.

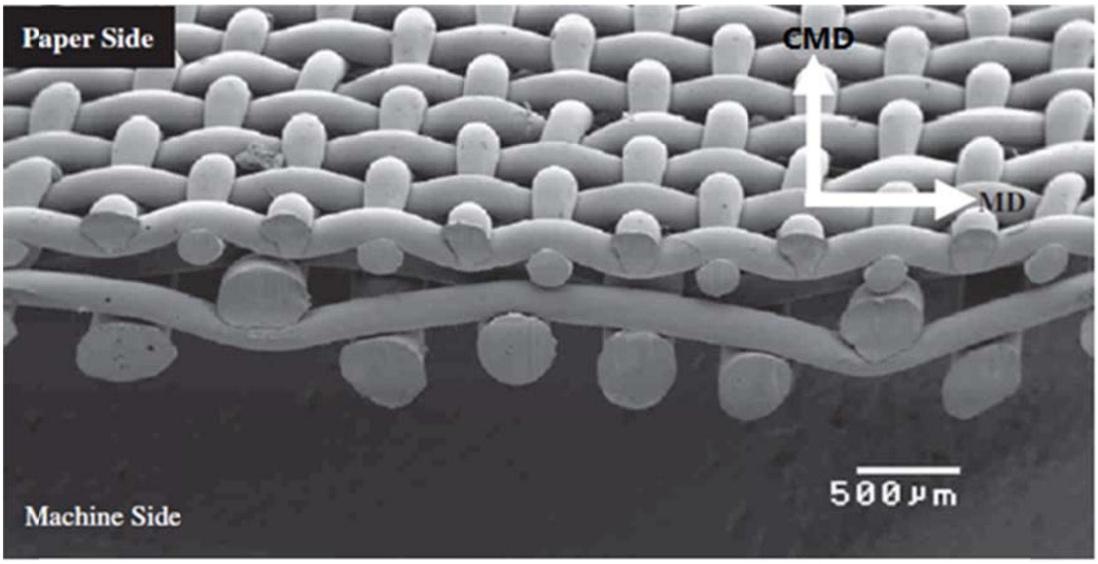

Fig.1. A micrograph showing the two sides of a forming fabric

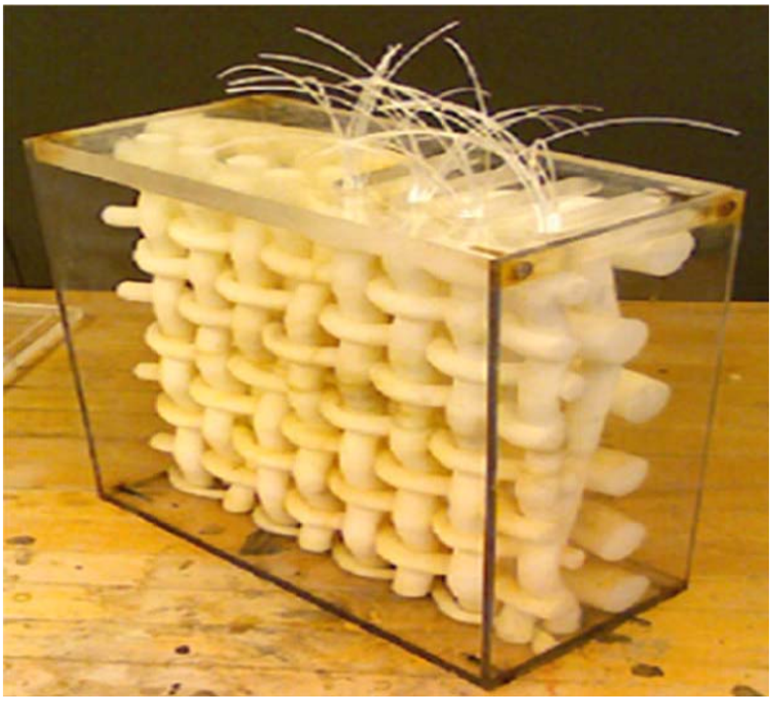

Fig.2. Scale model of forming fabric

EXPERIMENTAL METHODS

The experiments were conducted in the University of British Columbia, Pulp and Paper Center water/glycerin flow loop. The loop can provide velocities from 1.5 to 8 cm/s in the 30cm × 30cm test-section. By using a glycerin solution with a dynamic viscosity between 10 to 25 cP, and an 80 times-scaled fabric model, the test-section Reynolds number lies in the range from 10 to 65.

A schematic of the flow loop is shown in Fig.3. An image of the test-section with forming fabric installed is shown in Fig.4. And the schematic of PIV optical setup is shown in Fig.5. The flow was seeded with 20μm hollow glass bead. The pulse laser beam generated by a New Wave GEMINI™ laser head was transformed to a 1mm thickness laser sheet by a cylindrical lens. The synchronized PIV camera then grabbed pairs of image of the illuminated laser sheet in a short time interval. Using Dantec FlowManager™ software to analyze the image, we obtained the velocity distribution on the plane illuminated by laser sheet. With a linear slide, the velocity distribution at different laser sheet planes, i.e. different CMD planes, could be measured without adjusting the camera focus. This is convenient for data collection and data analysis since the dimensions of the field of view are always the same.

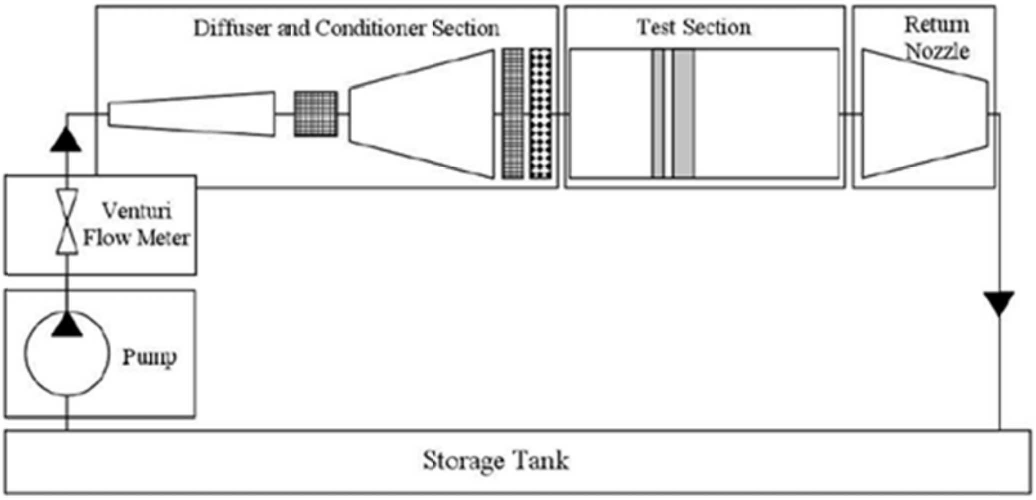

Fig.3. UBC Pulp and Paper Center water/glycerin flow loop

Fig.4. 30cm×30cm test section with forming fabric installed

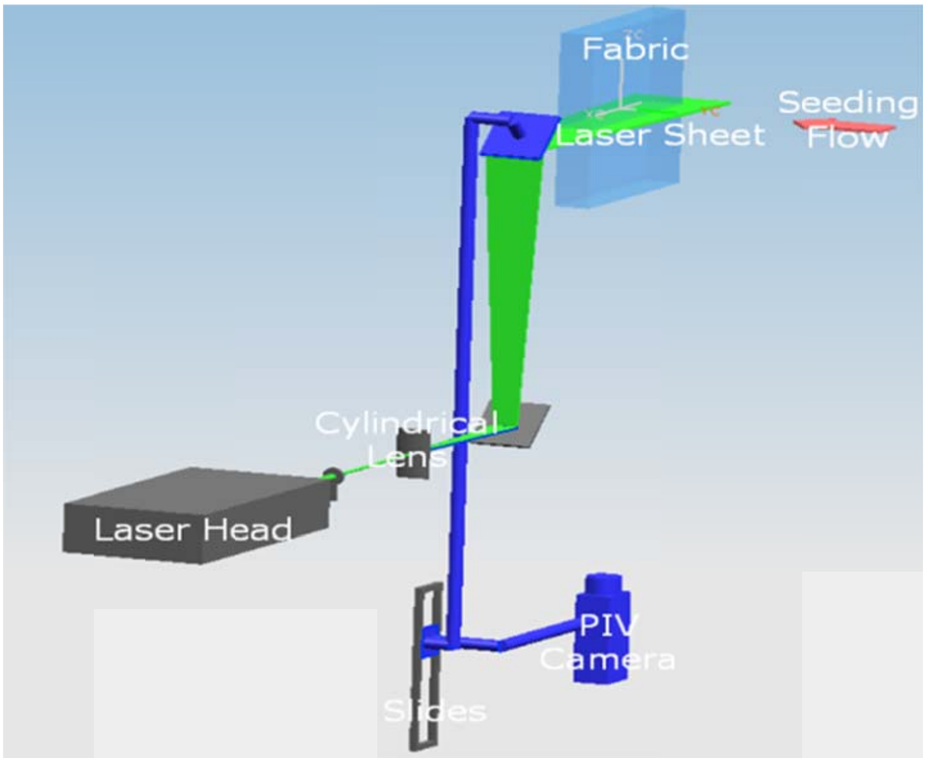

Fig.5. Optical setup of the PIV experiment

PIV RESUTLTS AND DISCUSSIONS

PIV measurements were conducted for different CMD plane, shown in Fig.6, at different Reynolds number. In order to keep the plots uncluttered only Fig.7 has uncertainty bars, which represent the 95% confidence interval, based on 60 PIV image pairs for each configuration. The plots were smoothed using a moving average by the curve fitting toolbox in MATLAB. The MD distance is normalized by the thickness of the fabric model. For this scaled model using in the flow loop, it is a portion smaller than one fabric repeat, and the MD length is about 3.1 times of the fabric model's thickness. To avoid contamination of the results by wall boundary layer effects, only the portion of the fabric away from the test section walls was studied.

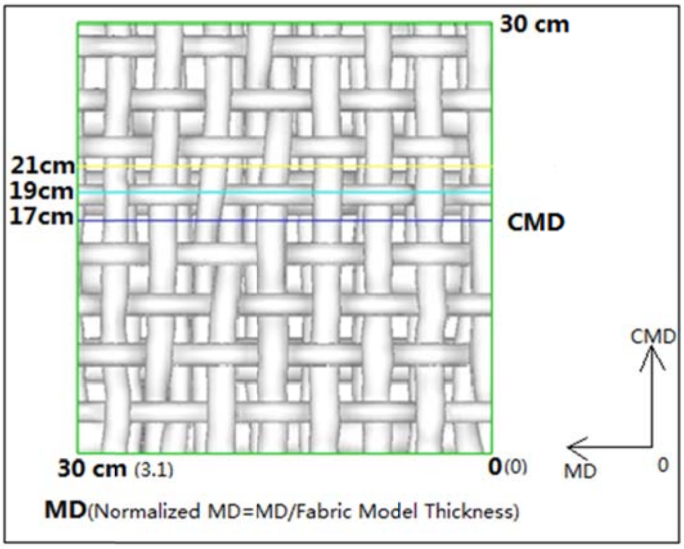

Fig.6. MD-CMD view of the scaled fabric model

Fig.7 shows that the RMS variation of MD velocities are about 10% of the average Z direction velocity at a distance 0.25d (d=paper side filament diameter) above the fabric. The highest uncertainty for Z direction velocity in the MD line is ±2.8%. In view of the fact that the fiber mat density distribution is mainly determined by the Z direction velocity distribution, only the Z direction velocity component will be analyzed and plotted in subsequent figures.

Fig.8 shows that the deviation of the Z direction velocity decreases from 15.1% at a plane 0.25d upstream the forming fabric to 3.8% at a plane 1.5d upstream. This means that the flow non-uniformity caused by the forming fabric is only significant within about 1.5 paper-side-filament-diameters upstream of the forming fabric.

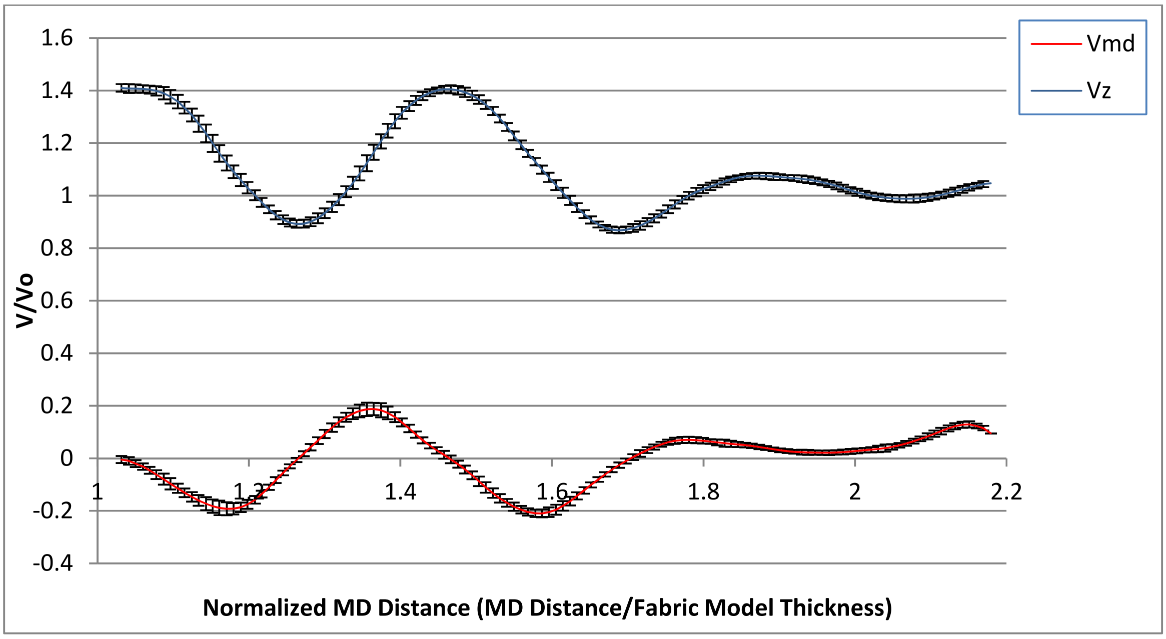

Fig.7. Normalized Velocity as a function of normalized MD distance, at the location CMD=17cm, 0.25d upstream of the fabric model; Re=35

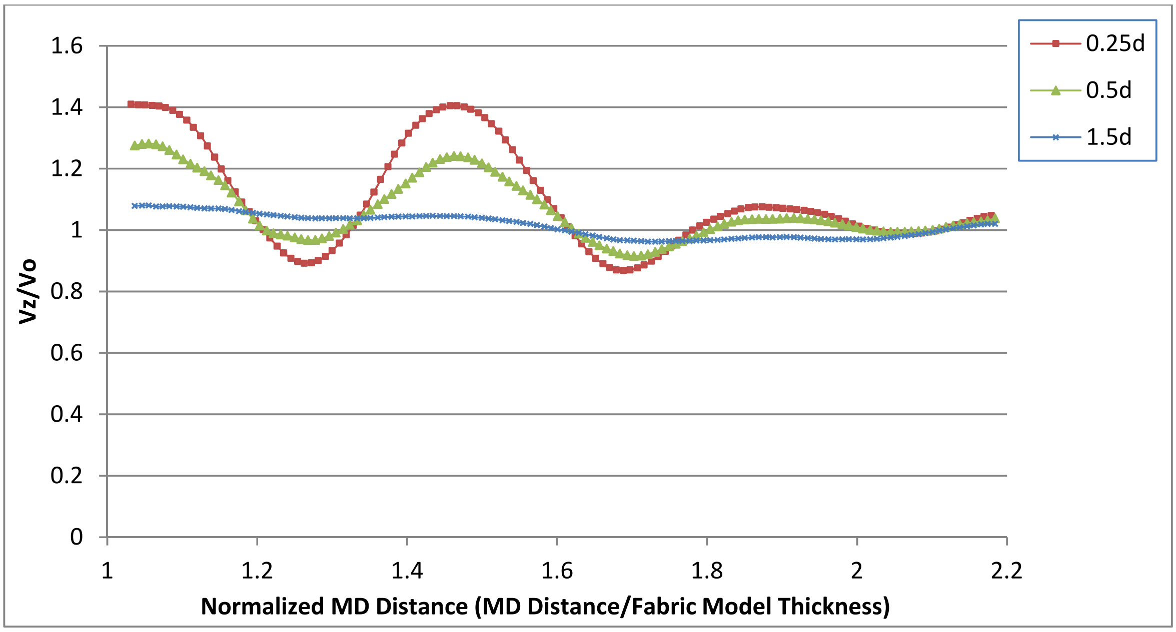

Fig.8. Z direction Velocity distribution for different distances upstream of the fabric model; CMD=17cm, Re=35

Fig.9. shows the velocity profile at two different CMD planes: CMD=17cm (the plane with multiple open areas) and CMD =19cm (the plane with multiple filament knuckles); refer to Figure 6. The highest Z direction velocity ($1.41V_o$) is about 2.2 times the lowest Z direction velocity ($0.65V_o$). Because fines and fillers are relatively tiny and nearly follow the flow (neglecting their interaction with fibers), the PIV result implies that there are areas over which the initial accumulation of fines and/or filler content can be 2.2 times higher than in adjacent areas. Once fines and fillers start to accumulate on the fabric, the "healing effect" will reduce the magnitude of this variation. This finding is consistent with the results of Vakil et al. [1].

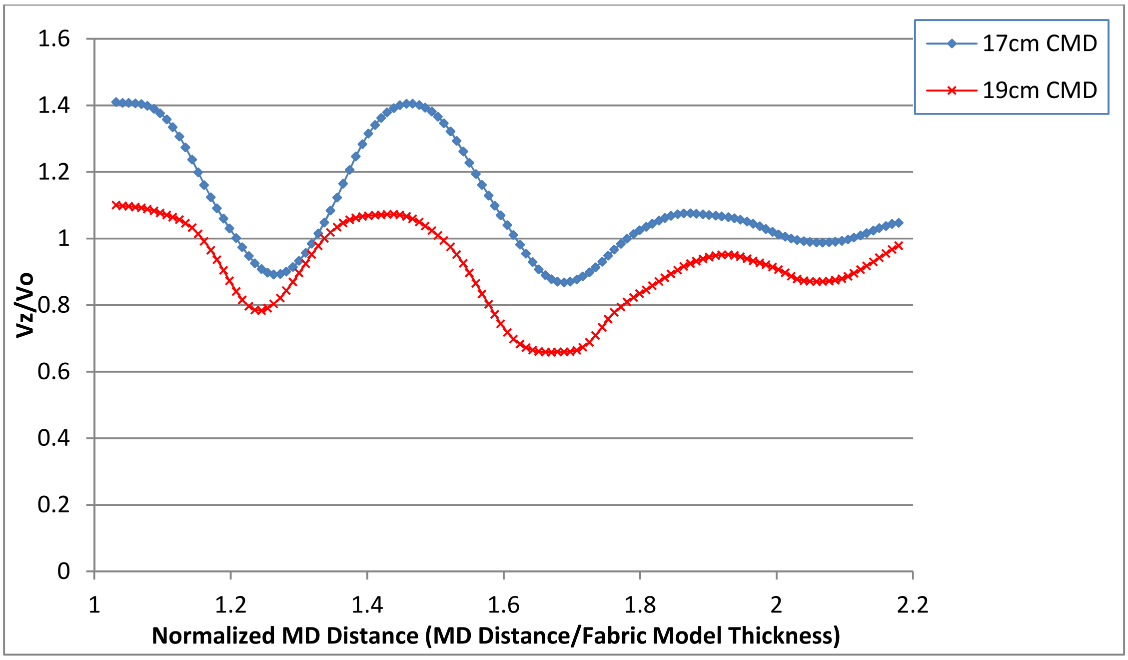

Fig.9. Z direction velocity distribution on different CMD plane, 0.25d upstream, Re=35

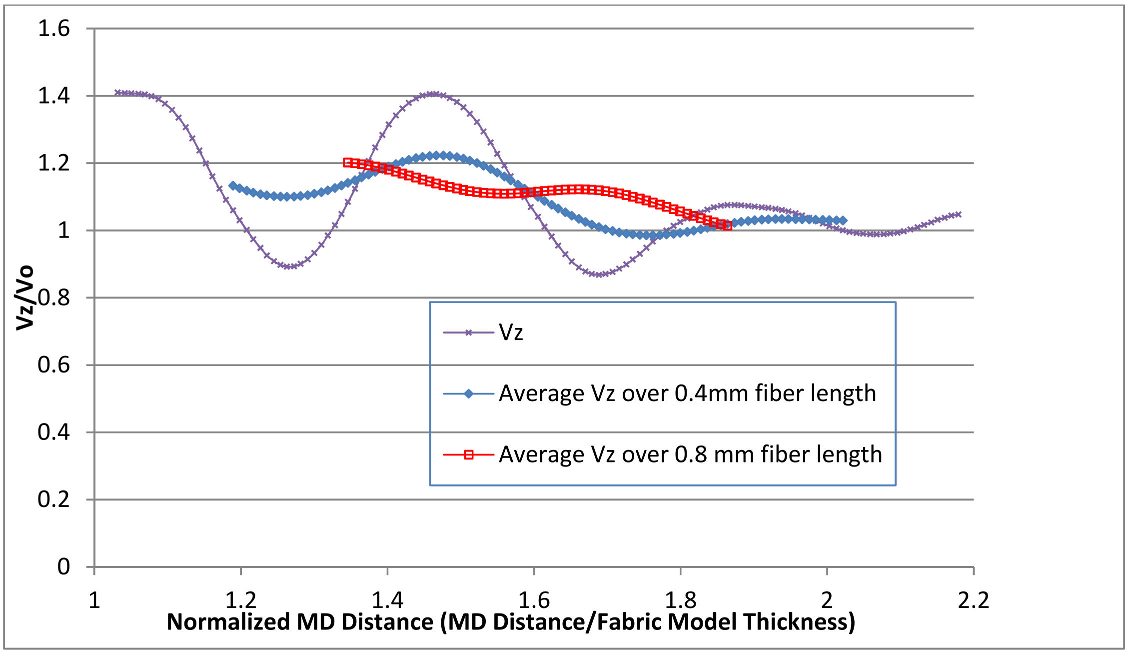

Fig.10. Z direction velocity averaged over different fiber length in MD, 0.25d upstream, CMD=17cm, Re=35

Since pulp fibers have a length scale that is longer than the forming fabric filament spacing, they are exposed to flow field forcing that is related to the average velocity along the fiber length. Here we assume a fiber 0.8mm long is oriented parallel to MD and we average over a MD line with length equal to the fiber length. With this averaging (Fig.10), the velocity deviation is reduced from 15.1% to 4.2%. Many wood fibers are longer than 0.8mm, for which the averaging effect would be greater still, and we can therefore predict that provided fibers were uniformly distributed in the approach flow, they would remain so during interaction with this forming fabric.

Fig.11 shows the Z direction velocity profile at two different Reynolds numbers. The standard deviation for a Reynolds number of 65 is 16% lower than the deviation for Reynolds number 15. The reduced standard deviation is consistent with the fact that the distance over which objects affect flow is smaller at higher Re.

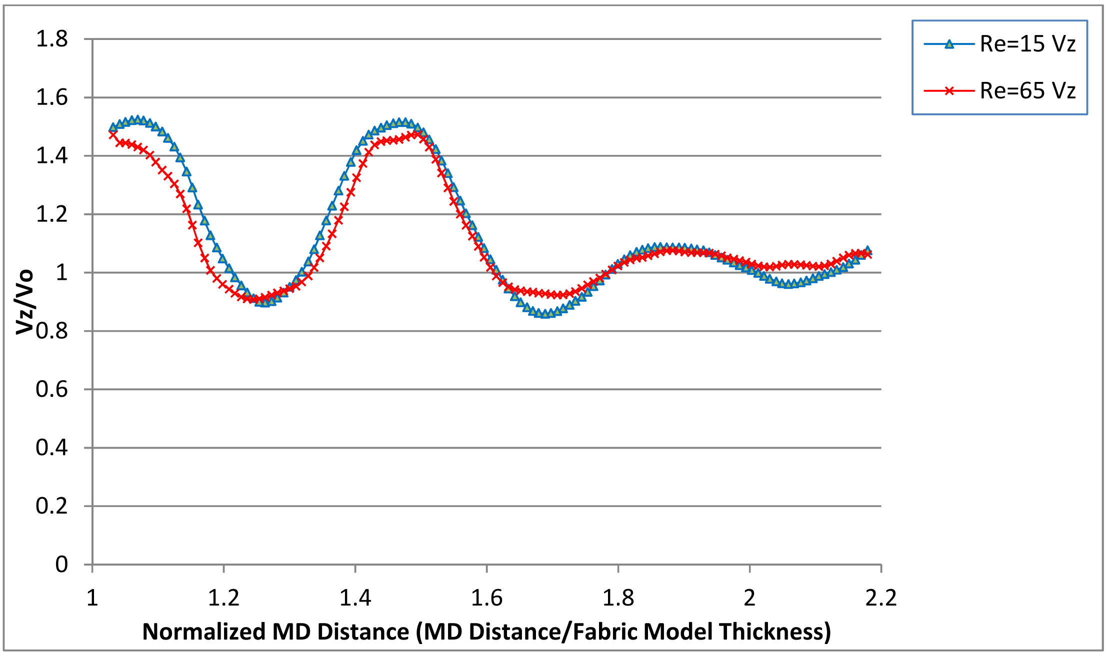

Fig.11. Z direction velocity profile for different Reynolds number, 0.25d upstream, CMD=17cm

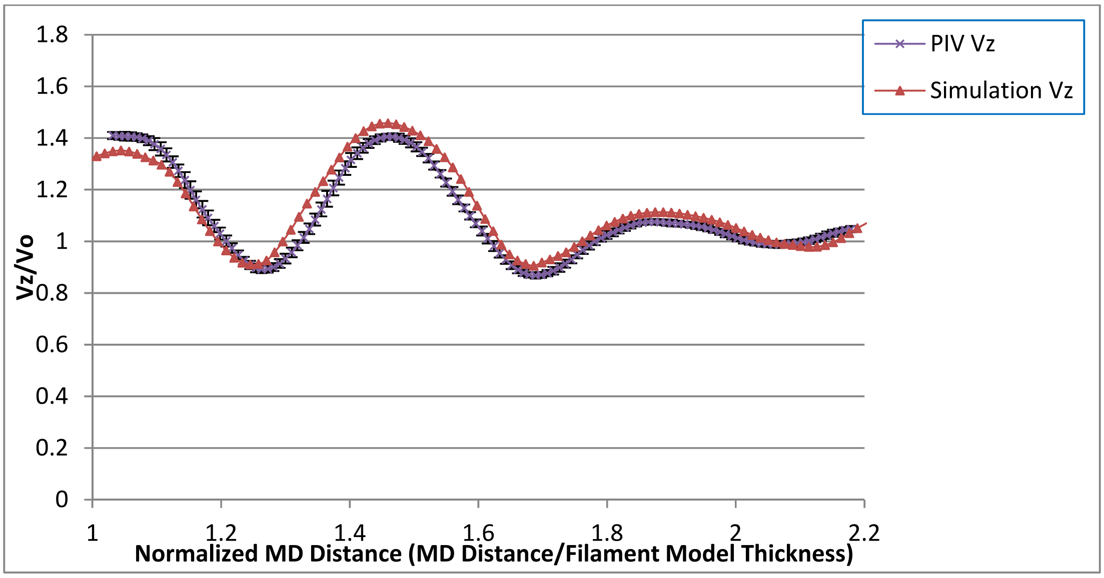

Fig.12. Comparison between Simulation and PIV measurements for Z direction velocity distribution, 0.25d upstream, CMD=17cm, Re=35

CFD simulations were done of the flow through the same fabric model using FLUENT^{TM} with the methods described by Green et al. [6]. As shown in Fig.12, the simulation result is very close to the PIV measurements and never differed by more than 9%. Simulations conducted at higher and lower Reynolds numbers were also in fairly good agreement with the experimental measurements.

CONCLUSIONS

PIV measurements of flow through a particular woven fabric at the Reynolds numbers typical of papermaking have been performed. It showed that the RMS variation of machine direction velocities are about 10% of the average Z direction velocity at a distance 0.25d above the fabric. The deviation of the Z direction velocity decreases from 15.1% at a plane 0.25d upstream forming fabric to 3.8% at a plane 1.5d upstream fabric, which means that the flow non-uniformity caused by the fabric weave is constrained to a short distance above the fabric. The local Z direction velocity varies by up to a factor of 2.2 from zenith to nadir, which indicates that there are areas over which the fines and fillers initially accumulate 2.2 times faster than in adjacent areas. However, this non-uniformity is not particularly felt by fibers, whose length scale results in averaging of the local velocity field. The Z direction velocity variation decreases by 15.5% when the Reynolds number is increased from 15 to 65. CFD simulations of the same flow were consistent with the PIV measurements within $\pm$ 9%.

For industry application, we can use this method to measure the velocity distribution in the vicinity of a forming fabric. This velocity distribution causes the localized redistribution of fines and filler material in the fibre mat near the wire side. Different fabrics will have different velocity distributions and therefore different effects on the fines and filler distribution in the finished paper. By better understanding the velocity distributions of fabrics we may then design fabrics that produce a superior (more uniform) distribution of fines and fillers in the finished paper.

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References

[1]. Adanur, S., 1997. Paper Machine Clothing. Asten, Inc, Basel, Switzerland.

[2]. Danby, R., 1994. The impact of forming fabric structures on print quality. Pulp & Paper Canada, 95(1), 48-51.

[3]. Danby, R., Plouffe, P., 2000. Print quality improvement through forming fabric design changes. Pulp & Paper Canada, 101(9), 66-69.

[4]. Johnson, D.B., 1984. Retention and drainage of forming fabrics. Pulp & Paper Canada, 85(6), T167-T172.

[5]. Johnson, D.B., 1986. Retention and drainage of multi-layer fabrics. Pulp & Paper Canada, 87(5), 56-59.

[6]. Vakil, A., Olyaei, A., Green, S., 2009. Three-dimensional geometry and flow field modeling of forming fabrics. Nordic Pulp and Paper Research Journal. vol.24 no.3, 342-250.

[7]. Dalpke, B., Kerekes, R., Green, S., 2004. Modeling jet impingement and the initial drainage zone in roll forming. Journal of Pulp and Paper Science 30, 65-70.

[8]. Huang, Z., 2003. Numerical simulation of flow through model paper machine forming fabrics. Master's Thesis, The University of British Columbia, Vancouver, British Columbia, Canada.

[9]. Huang, Z., Olson, J., Kerekes, R., Green, S., 2006. Numerical simulation of the flow around rows of cylinders. Computers & Fluids 35,485-491.

[10]. Gilchrist, S., Green, S., 2009. Experimental investigation of flow through bank of cylinders of varying geometry. Journal of Fluids and Structures 25, 506-518.

[11]. Green, S., Wang, Z., Waung, T., Vakil, A., 2008. Simulation of the flow through woven fabrics. Computer & Fluids 37, 1148-1156.