Aerodynamics of high-speed paper machines

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ABSTRACT

Dryer geometry, dryer clothing, and blow boxes affect the aerodynamic flow in a paper machine dryer. Laser doppler velocimetry and computational fluid dynamics provided a study of air flow conditions in critical areas near a paper sheet. New blow box and fabric designs offer better sheet runnability in the dryer section of high-speed paper machines.

Application:

New methods for analyzing and improving sheet runnability suggest new blow box and fabric designs for paper dryers.

THE AERODYNAMIC FLOW PATTERN is an important factor influencing sheet runnability in the dryer section of a high-speed paper machine. Three main parameters affect the aerodynamic flow pattern in the paper machine dryer section:

- Dryer geometry (cylinders, rolls, and fabric run)
- Dryer clothing (type of fabric)
- Air-handling devices (blow boxes).

This paper presents research to develop a fundamental understanding of the interaction of these parameters. Our work also showed how the resulting aerodynamic flow pattern in the dryer section affects runnability in high-speed paper machines running over 2000 m/min. Using advanced state-of-the-art measurement and computer simulation techniques, we studied air flow conditions in detail in the critical areas near the paper sheet.

The research has established new methods for analyzing and improving sheet runnability. In addition, it has suggested new blow box and fabric designs for paper dryers.

METHODS

The program used a pilot paper machine operating at 2000 m/min with a fabric width of 600 mm for the aerodynamic measurements. The pilot machine originally ran paper machine press felts. It has a press nip and turning rolls. To achieve a two-dimensional air flow pattern and minimize boundary effects due to the narrow web width, we mounted transparent plastic sheeting on both sides of the machine. **Figure 1** shows the configuration of the pilot machine. The design of the flexible framework simulates a modern high-speed paper machine with single-tier run and a vacuum roll system.

Dryer fabrics and blow boxes

The dryer fabrics used in the tests had different designs specifically for high-speed paper machines. They were proven fabrics with well-known running characteristics. We also used some new, experimental designs.

Most tests used fabrics with a permeability of 1500 meters^3/meters^2·h (95 ft^3/min). This value has been the standard for no-draw applications. Because new design dryer sections are using fabrics of increasing permeability, tests included permeabilities of 0–10,000 meters^3/meters^2·h (0–625 ft^3/min).

A study of differently designed air control blow boxes studied how the interaction of the geometry of the blow box, the operating conditions, and the blow box with different dryer fabrics affects the flow pattern. Using this data, we developed technology for a new generation of blow boxes meeting the requirements of high-speed paper machine geometries for effective sheet control.

LDV measurements

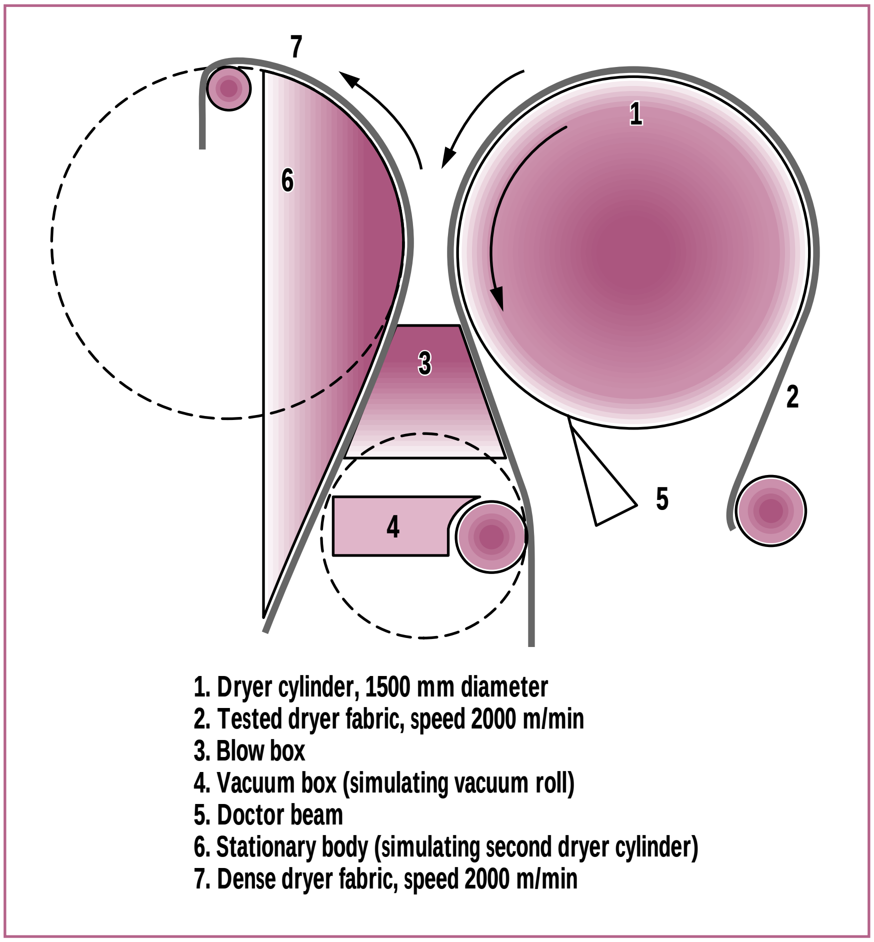
A fiber optic laser Doppler velocimetry (LDV) system measured the air flow[1]. This technique uses two laser beams from a common lens system crossing in a probe volume to create an interference pattern. When an airborne particle passes through the probe volume, the light reflected by the particle provides information about the velocity in a single direction perpendicular to the beam path. Using an additional set of laser beams with a different wave length in the same lens system oriented perpendicular to the first one provides information about the velocity in two dimensions simultaneously.

Since the measured velocities are for artificially supplied particles—seeding particles—rather than the air itself, one must assume that the particle velocities are identical to the air velocities. To achieve this, the seeding particles must be small enough to have a negligible moment of inertia to accelerate with the air flow. The seeding particles used in our tests were olive oil droplets with a mean diameter of approximately 0.6 μm.

The size of the probe volume was approximately 0.1 x 3 mm. This allowed us to measure the air velocity close to the moving surfaces in the pilot paper machine.

The main advantages to LDV technology over other methods are

[1]Adrian, R. J., in *Laser Velocimetry, Fluid Mechanics Measurements* (R. J. Goldstein, Ed.), Springer-Verlag, New York, 1983, pp. 155-244.



1. The flexible framework of the pilot machine configured to simulate the geometry of a modern high-speed paper machine having a single-tier run and a vacuum-roll system, with broken lines indicating the location of the second cylinder and the vacuum roll

the following:

- Makes nonintrusive measurements of air mean velocities and turbulence intensities
- Obtains velocity data in well-defined directions
- Measures air mean velocities and turbulence intensities near moving surfaces.

CFD simulations

Computational fluid dynamics (CFD) simulations of the flow in the pilot machine geometry supplemented the LDV measurements. In this technique, a complex set of differential equations describing the relationships between local fluid velocity components, U, V, and W, and local pressure, p, govern general fluid flow in three dimensions. These equations are the Navier–Stokes equations.

In practical applications, most ordinary flows are turbulent. This means the flow exhibits random fluctuations in time. To simplify the analysis of turbulent flows, it is possible to divide the flow pattern into a steady, time-independent part—the Reynolds averaged equations—and a fluctuating part. The time-independent part describes the time-averaged mean flow pattern corresponding to the measured mean velocity components. The effect of fluctuations on the mean flow enters through the use of a turbulence model. A turbulence model deals with velocity fluctuations in statistical terms such as turbulence intensities measured as root-mean-square (RMS) values of velocity.

In CFD, the geometry of the flow domain is generally divided into a grid of rectangular cells. The original differential equations can be approximated with a system of ordinary equations describing the relationships among the variables in all grid cells. These equations are nonlinear and require effective numerical methods for solution.

In the CFD simulations of the flow in the pilot machine, we assumed the sheet run was wide enough for the flow pattern to be approximately two dimensional. We used the time-averaged Reynolds equations to describe the mean flow pattern. Using the standard k–ε model allowed us to model the effect of turbulence and gave us two additional variables—turbulent kinetic energy, k, and turbulence dissipation rate, ε.

The modeled geometry was identical to that of the pilot paper machine. We compared measurements and model predictions in some cross sections to verify the performance of the simulation model and establish a baseline for future improvements of the models.

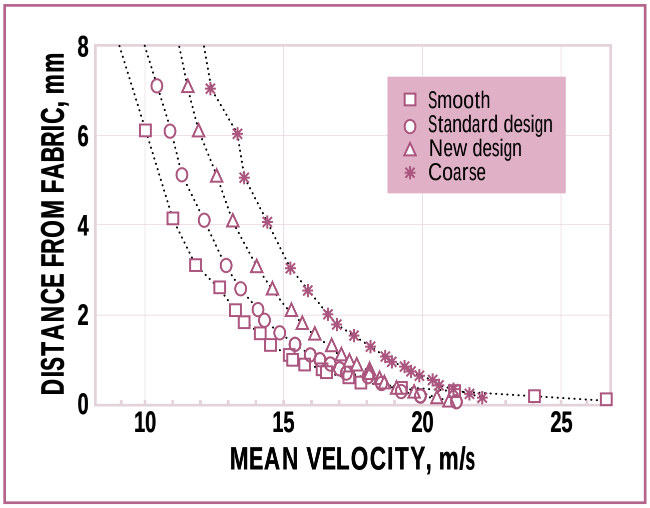
RESULTS

Boundary layer measurements

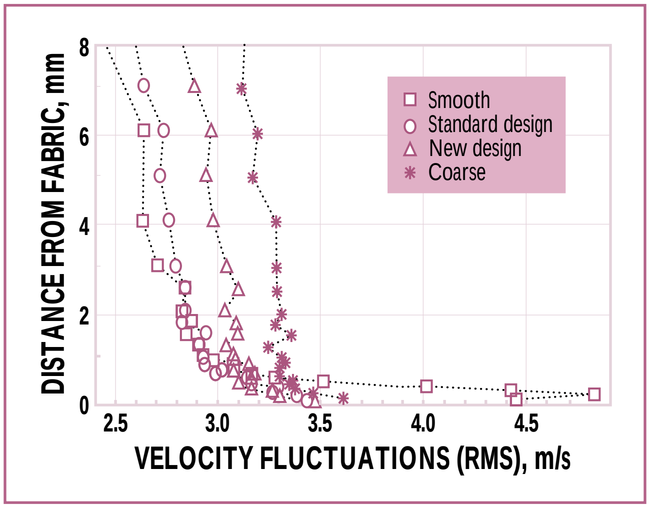
Friction forces on the surfaces of the moving fabrics will act on the surrounding air, causing an accumulation of a boundary layer around the surface of the fabric. The thickness of the boundary layer increases with the distance traveled from the starting point. The pilot machine had a long horizontal draw for the boundary layer measurements.

The boundary layer measurements used a machine speed of 2000 m/min (33.3 m/s) in a position where the boundary layer had developed for 1750 mm. A steel sheet supported the fabric to avoid permeability effects and vertical movements of the fabric.

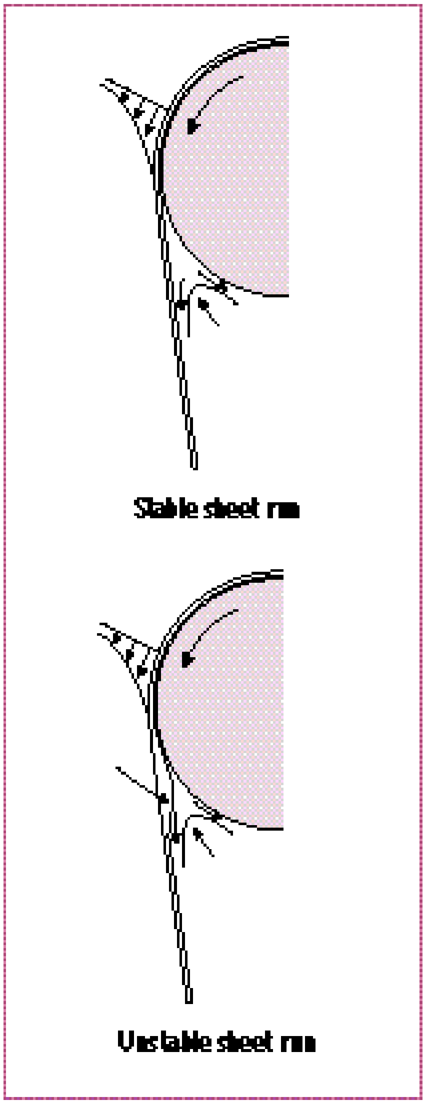
Figures 2 and 3 show the boundary layer velocity and the boundary layer turbulence level, respectively. The fluid seems



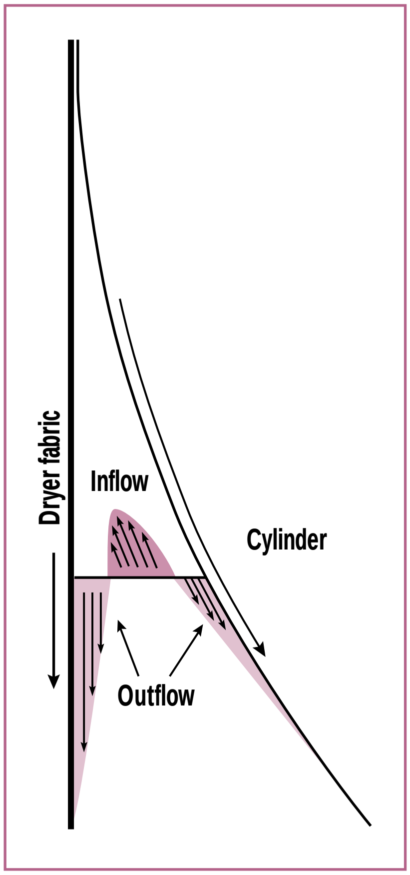
2. Boundary layer mean velocity



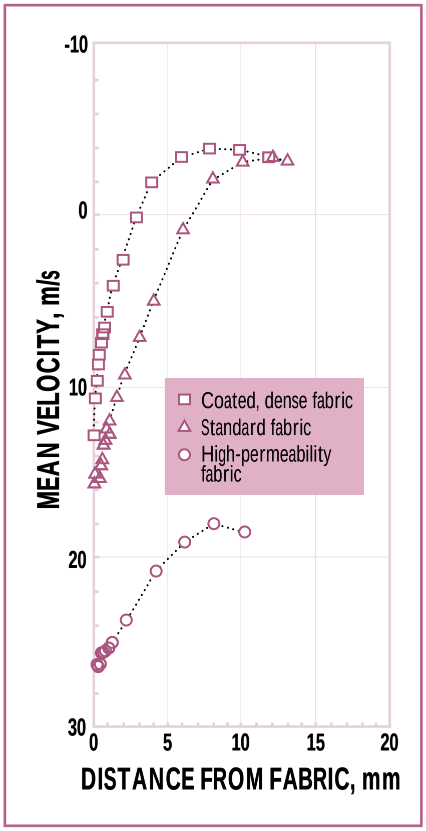
3. Boundary layer turbulence level in RMS values



4. Stable and unstable sheet runs in diverging nip



5. Illustration of the flow pattern in the measurement cross section in the diverging nip

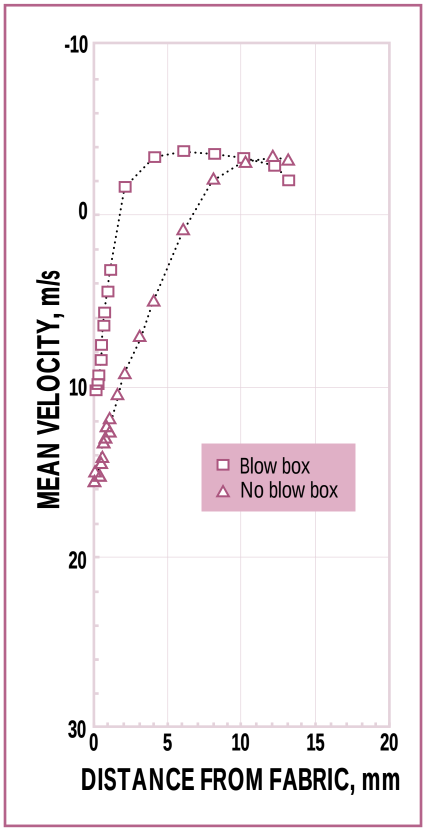


6. Mean velocity profiles in the diverging nip for fabrics with similar structure but different permeability

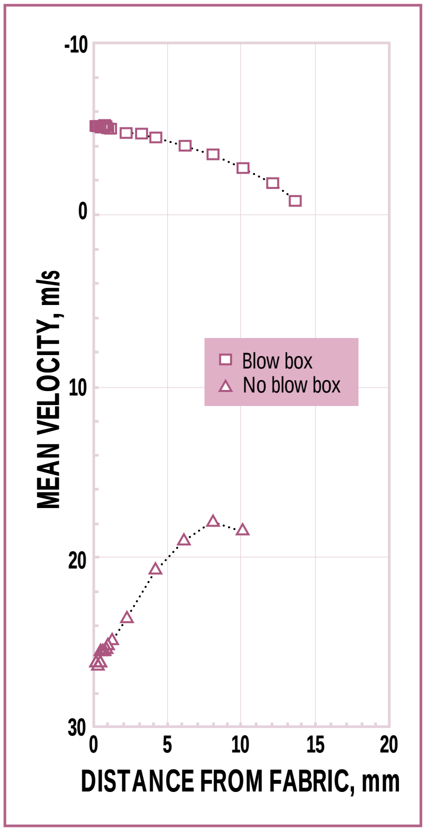
attached to the smooth surface, while it appears to slip on the fabric surfaces. Note that a smoother surface has less air transported in the boundary layer.

Diverging nip measurements

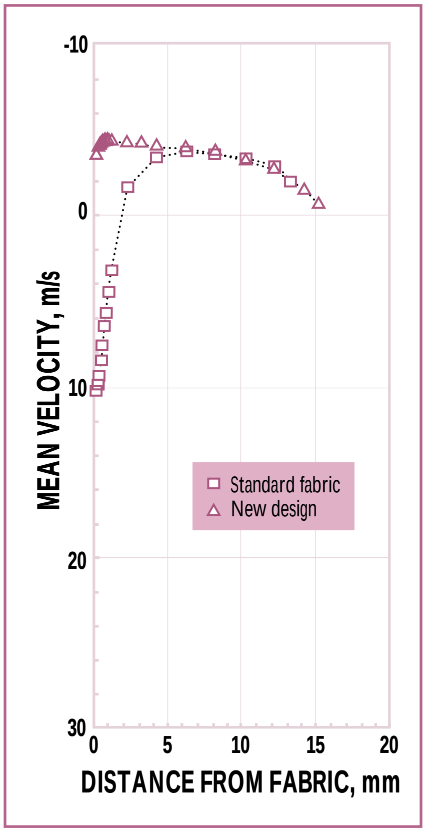
The diverging nip where the paper sheet and dryer fabric leave the dryer cylinder is critical to the runnability of the paper machine in a single-tier geometry. Because of adhesion forces between the wet



7. Mean velocity profiles in the diverging nip with and without a blow box using a standard fabric with a permeability of 1500 m³/m²·h



8. Mean velocity profiles in the diverging nip with and without a blow box and a fabric with high permeability of 6000 m³/m²·h showing the more pronounced effect of a blow box



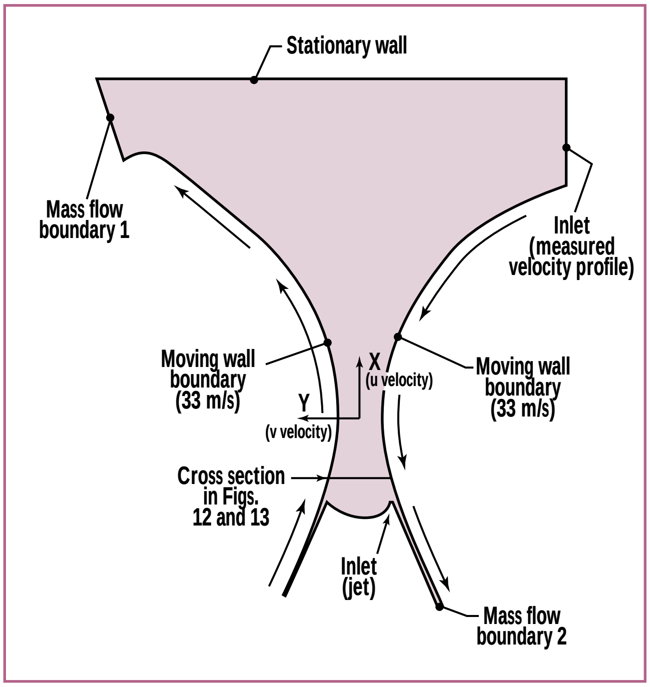
9. Mean velocity profiles in the diverging nip with blow box and a fabric with new design compared with a standard design of the same nominal permeability of 1500 m³/m²·h

paper sheet and the smooth cylinder surface, the paper sheet tends to follow the cylinder for a short distance. The volume created between the fabric and the paper sheet allows air transport through the fabric. The transportation of air through the fabric aggravates sheet flutter, as **Fig. 4** shows. Aerodynamic forces acting on the paper sheet through the permeable fabric cause this behavior.

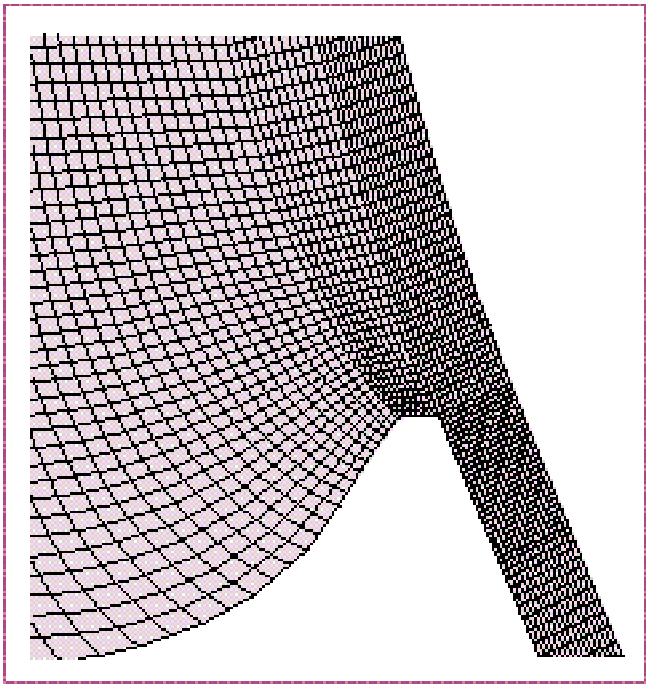
Parameters such as the dryer fabric structure, fabric permeability, and the design and operation of blow boxes affect the transport of air through the dryer fabric and the contribution to sheet flutter. In the pilot machine tests, we made LDV measurements to study and optimize these parameters. We did the measurements without a paper sheet present to concentrate on studying the air transported through the fabric. This air flow through and around the fabric, with a principal flow pattern indicated in **Fig. 5,** is the result of the pressure forces acting on both sides of the paper sheet when it is present. Fig. 5 illustrates the flow direction in a cross section in the outgoing nip. In **Figs. 6–9**, a positive mean velocity normal to this cross section corresponds to an outflow from the diverging nip, and a negative velocity corresponds to an inflow.

Figure 6 shows the air flow pattern in the diverging nip close to the fabric surface for fabrics with different permeabilities but similar structure. Permeabilities are 0, 1500, and 6000 m³/m²·h for the coated, standard, and high permeability fabrics, respectively. The coated impermeable fabric is the reference, since there is no flow through the fabric. Flow patterns with the permeable fabrics indicate a net flow of air transported through the fabric. The coated impermeable fabric shows a well-defined boundary layer following the fabric away from the diverging nip. Since the coated fabric is impermeable, the boundary layer must be fed with air from the center of the diverging nip. Permeable fabrics show a greater outflow than inflow. This means that the balance must be kept with air transported through the fabric.

Air control blow boxes are a very efficient way to minimize or even reverse the air flow through the fabric. Figure 7 shows the flow pattern in the diverging nip with and without a blow box using a standard fabric with a permeability of 1500 m³/m²·h. With the blow box in operation, the inflow is approximately equal to the outflow. This indicates neutralization of the aerodynamic forces responsible for driving air through the fabric. The effect of a



10. Outline of CFD model geometry



11. Closeup of computational grid around the blow box nozzle tip

blow box is even more pronounced on a fabric with high permeability, as Fig. 8 illustrated for a fabric permeability of 6000 m³/m²·h.

Fabric permeability is not the only parameter influencing the performance. The design of the fabric is also important. Using an optimal combination of fabric and blow box designs to control and balance the aerodynamic forces provides the best improvement of sheet stability. Figure 9 compares the effects of a blow box on a new fabric design with the effects on a standard fabric. The performance of the novel fabric design is significantly better, although the two fabrics have the same nominal permeability of 1500 m³/m²·h.

The tests showed that a new generation of blow box and fabric designs could create a diverging-nip flow pattern that attaches the sheet to the fabric at machine speeds of 2000 m/min. With the optimized test system, the inflow to the nip is obviously far greater than the outflow. The pressure differences over the fabric drive the balance of the air flows. In the tests, reversing the pressure difference had the same effect that normally causes sheet flutter, giving a positive impact instead. In an actual paper machine, the paper sheet would firmly attach to the dryer fabric.

CFD simulations

We modeled the geometry of the pilot machine with one blow box design in two dimensions using a commercially available CFD software package running on a standard workstation. We carried out simulations both with and without the blow box jet in operation.

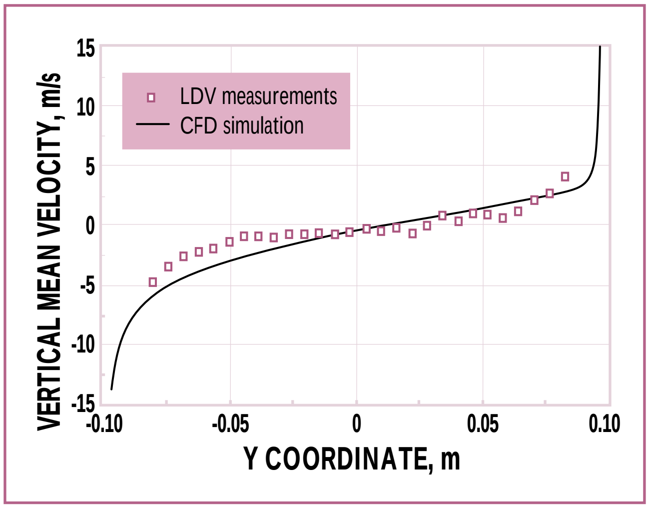
Figure 10 shows an outline of the CFD model including the types of boundary conditions used. The computational grid contains 19 blocks with more than 23,000 cells. **Figure 11** is a closeup of the grid around the blow box nozzle tip.

The velocity components in the inlet boundary in the upper right part of the model took values based on LDV measurements. We estimated the inlet profile of turbulent kinetic energy from measured velocity fluctuations—RMS values. We carefully adjusted the inlet profile of the turbulence dissipation rate—closely related to the length scale of turbulent eddies—to give a smooth downstream development of the turbulence quantities. In addition, we determined the ratio of the outlet mass fluxes in the two mass-flow boundaries in the upper left and lower right corners of the model from LDV measurements.

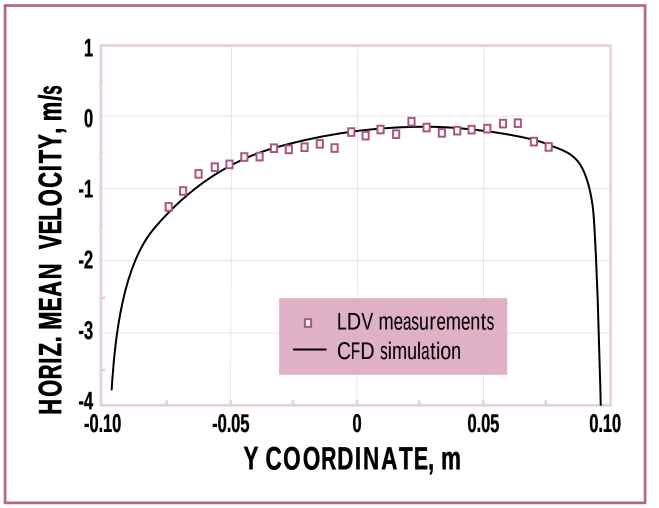
The moving fabric surfaces were modeled as wall boundaries with appropriate wall velocities and assumed to be hydraulically smooth. This is a simplification because we know from the boundary-layer measurements that an accurate description of the fabric boundary layers must account for the roughness and surface structure of the fabric.

Figures 12 and 13 compare the CFD model predictions with measurements in a cross section in front of the blow box with no jet in operation. Figure 10 indicates the location of the cross section. The horizontal velocity shows excellent agreement, and the vertical component is also acceptable.

A small set of measurements off the center plane of the pilot machine showed that weak three-dimensional effects caused by the limited width of the machine and the side walls were the same magnitudes as the deviations between measurements



12. Comparison of CFD model predictions with measurements in a cross section in front of the blow box for the location of the cross section indicated in Fig. 10



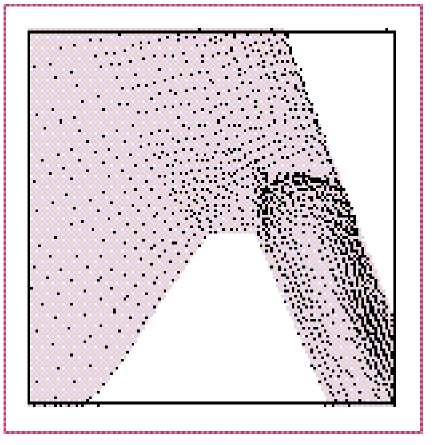
13. Comparison of CFD model predictions with measurements in a cross section in front of the blow box for the location of the cross section indicated in Fig. 10

and simulations. Other measurements closer to the fabric surface also differed from the simulations. These small differences are consistent with the assumption of smooth surfaces.

The most important function of the blow box is to reduce the pressure on the fabric side of the sheet run in the region of the diverging nip. There is a corresponding reduction of the pressure difference driving air through the fabric. We connected a pressure gauge to a pressure reference hole in the blow box 150 mm downstream from the nozzle tip to monitor the static underpressure created by the blow box compared with the ambient. We compared this pressure with the underpressure predicted in the simulations.

Without the jet in operation, the simulation predicted an underpressure of 70 Pa—excellent agreement with the 65 Pa measured in the experiments. With the jet in operation, the underpressure predicted by the simulation was approximately 300 Pa. Measurements showed only 165 Pa.

The most important reason for the deviation between simulation and experiment in the latter case is incorrect prediction of the behavior of the jet in the simulation. **Figure 14** shows the flow pattern in the region of the jet predicted in the simulation, with the recirculation of the jet confined to the nozzle tip. LDV measurements close to the blow box suggested that the jet in this design tilted up toward the nozzle tip and created a larger recirculation zone around the tip. The simple jet boundary conditions imposed in the present CFD model cannot emulate this deflection of the jet.



14. Flow pattern in the region of the blow box jet predicted by the simulation

CONCLUSIONS

Our development work in dryer aerodynamics provides fundamental facts for understanding the influence of all flow conditions on sheet runnability in the dryer section of a high-speed paper machine. The work offers a base for future development.

CFD provides an advanced tool for simulating complex flow phenomena. The application of CFD to actual engineering problems shows great promise because of the rapid development of computer hardware and computational methods. A future goal would be development of the theoretical framework for use in a well-tuned simulation model. The simulation tool can then be a basis for the design of rebuilds and future dryer sections, including machine geometry, blow boxes, and dryer fabrics. **TJ**

KEYWORDS

Aerodynamics, air flow, blow boxes, computation, computers, drier sections, fluid dynamics, geometry, high velocity, machine clothing, paper machines, parameters, runnability, simulation.

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