TRANSIENT 2D PAPER WEB DRYING MODEL BASED ON CFD

By

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ABSTRACT

In the present article, a model combining the benefits of the small scale and large scale approaches towards modeling paper drying in a paper machine dryer section environment is described. The model is transient and two-dimensional, taking into account the MD and the thickness directions but neglecting the phenomena in the CD direction.

The combined model consists of two parts:

1. A large scale CFD model of the surroundings of the paper web solving the RANS equations
2. A specific-purpose small scale model for heat and moisture transport phenomena inside the paper web.

The model is aimed at predicting the drying process in a paper production environment. The present model can be combined with a separate paper web deflection model in order to simulate the drying process and the paper web runnability simultaneously.

NOMENCLATURE

c	heat capacity at constant pressure
D	water vapor diffusivity in air
k	thermal conductivity of air, kinetic energy of turbulence
h	specific enthalpy
J	moisture flux in the thickness (y) direction
J	moisture flux vector
MD	machine direction
q	heat flux in the thickness (y) direction
q	heat flux vector
Re	Reynolds number

t	time
T	temperature
U	machine speed
x	coordinate in the machine direction
y	coordinate in the thickness direction
Y	water vapor mass fraction, kg $\{H_2O\}$ / kg $\{air + H_2O\}$
z	moisture ratio in the paper web, kg $\{H_2O\}$ / kg {dry paper}
δ	paper web thickness
Δt	time step
Δx	grid spacing in machine direction
Δy	grid spacing in thickness direction
ε	vapor diffusion resistance coefficient in paper web
κ	moisture diffusivity in the paper web
λ	effective thermal conductivity in the paper web
μ	dynamic viscosity
ρ	density
φ	partial pressure factor due to the sorption effect
ψ	vapor diffusion resistance coefficient in paper web
ω	humidity ratio, kg $\{H_2O\}$ / kg {dry air}
$\nabla \cdot$	divergence operator

Subscripts:

eff	effective
i	grid node number in machine direction
j	grid node number in thickness direction
p	paper
sat	saturated
v	water vapor
w	liquid water

Superscripts:

n	time step number

INTRODUCTION

Paper web drying is a complex phenomenon, which is challenging to model due to the variety of length scales that are physically meaningful. The ratio between the physical length scales in the machine direction (MD) and the thickness direction is in the order of 10^5. This makes it difficult to find a modeling technique that adequately describes both the small scale and the large scale phenomena.

A big portion of the academic research on web drying is concentrated on the small scale phenomena, such as the heat and moisture transport in the web. Very sophisticated models have been developed, which take into account vapor diffusion and capillary flow of free water in the web [0]. In these studies, the boundary conditions at the surface of the paper web have been mostly assigned based on experimental data.

On the other hand, computational fluid dynamics (CFD) has proven to be an excellent tool for the large scale simulations of the paper machine dryer section. The heat and moisture transport in the surrounding turbulent air flow is solved rather easily using standard commercial CFD software. However, rigorous CFD solution of the small scale phenomena in the paper web together with the large scale analysis of the surrounding air is not practical with the current computers and software.

Using a small scale model for the whole region would lead to a model that is too large to be solved in reasonable time with today's computers. On the other hand, using a large scale model for the whole problem would make the model too simplistic for predicting various physical phenomena present in the drying process. Thus, a natural idea is to try to combine the benefits of the small and the large scale models.

The large scale and the small scale models were previously combined by some of the present authors [0]. However, their model is only applicable in the steady state. Furthermore, the small scale paper web model is one-dimensional, totally neglecting the transport phenomena in the thickness direction.

The present paper aims at obtaining a transient model for paper web drying where both the large scale and the small scale models are two-dimensional. In the present paper the heat and moisture transport phenomena are modeled in the thickness direction on top of the MD direction.

MODEL STRUCTURE

Due to the very different length scales required for modeling the transport phenomena in the paper web and the exterior flow field, it is impractical to treat these phenomena with a single modeling approach.

The solution is to use different methods for simulating different phenomena. The principle of the combined model is shown in Figure **Error! Reference source not found.**. Data exchange between the submodels needs to be organized such that the two models together work in the desired way.

The large scale phenomena, such as the air flow and the heat and water vapor transport in the surrounding air, are solved with the commercial computational fluid dynamics (CFD) software ANSYS Fluent.

In contrast, the small scale heat and moisture transport phenomena in the paper web are solved using a proprietary C++ code. The data exchange between the two submodels is arranged using the user defined function (UDF) mechanism of the ANSYS Fluent software [0].

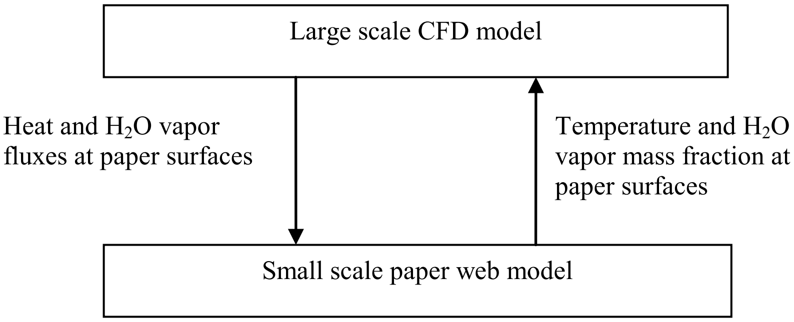

Figure 1 – Principle of the combined model

Figure **Error! Reference source not found.** also shows the principle of the data exchange between the models. At each time step, the instantaneous heat and water vapor flux fields simulated with the large scale CFD model are transferred to the small scale paper web model, where they are used as boundary conditions. Correspondingly, the temperature and the water vapor mass fraction fields at the paper web surfaces are simulated with the small scale model and transferred to the CFD model, where they are used as boundary conditions.

COMPUTATIONAL FLUID DYNAMICS MODEL

Since the full direct numerical simulation of the turbulent flow field is not practical with the current computers, the unsteady Reynolds averaged Navier-Stokes (URANS) equations are solved in order to obtain an approximate solution. The turbulence is modeled using the renormalization group theory (RNG) k-ε turbulence model [0].

In the near-wall model used by ANSYS Fluent, the viscosity-affected near-wall region is completely resolved all the way to the viscous sub layer [**Error! Reference source not found.**]. In the approach, the whole domain is subdivided into a viscosity-affected region and a fully-turbulent region, thus called the two layer model. The demarcation of the two regions is determined by a wall-distance-based, turbulent Reynolds number, Re_y, defined as,

$$\mathrm{Re}_y = \frac{\rho y \sqrt{k}}{\mu} \qquad \{1\}$$

where y is the normal distance from the wall at the cell centers. Other parameters are density, viscosity and the turbulent kinetic energy. In the viscosity-affected near-wall region ($\mathrm{Re}_y < 200$), the one-equation model of Wolfstein [0] is employed. The enhanced turbulent law-of-the-wall for compressible flow with heat transfer and pressure gradients has been derived by combining the approaches of White and Cristoph [0] and Huang et al. [0]. The enhanced wall functions were developed by smoothly blending an enhanced turbulent wall law with the laminar wall law. By securing sufficiently high resolution of the computational mesh at the surface of the wall it is possible to compute the velocity profile starting from the laminar sublayer of the boundary.

In the CFD model, the paper web is modeled as having zero thickness. The CFD model itself does not treat the small scale heat and moisture transport phenomena inside the paper web. Thus, the CFD model is referred to as "the large scale model".

However, the transport phenomena inside the paper web affect the results given by the CFD model due to the boundary conditions. The temperature and the water vapor mass fraction fields at both surfaces of the paper web are used by the CFD model at each time step as boundary conditions. This is implemented with ANSYS Fluent's user defined function (UDF) mechanism.

From the CFD simulation, the local heat and water vapor fluxes at both surfaces of the paper web are computed at each time step and passed for the small scale model to be used as boundary conditions:

$$q = k_{eff} \frac{\partial T}{\partial y} \qquad \{2\}$$

$$J = \rho D_{eff} \frac{\partial Y}{\partial y} \qquad \{3\}$$

where q and J are the heat and water vapor fluxes, respectively, while k_{eff} and D_{eff} are the effective heat conductivity and the effective diffusion coefficient, respectively. The effective values take into account both the molecular diffusion and the effects of turbulence.

SMALL SCALE PAPER WEB MODEL

Governing Equations

The small scale transport phenomena in the paper web are treated separately from the large scale CFD model. In the small scale model, the transient heat and moisture transport phenomena are modeled taking into account the thickness direction (y) on top of the machine direction (x). Thus, in the small scale model, the paper web has a finite thickness, although it is modeled as infinitely thin in the large scale CFD model.

Assuming the paper web as a continuum, writing the moisture and the energy balances for a differential control volume yields the following equations:

$$\rho_p \left(\frac{\partial z}{\partial t} + U \frac{\partial z}{\partial x} \right) = -\nabla \cdot \mathbf{J} \qquad \{4\}$$

$$\left(\frac{\partial}{\partial t} + U \frac{\partial}{\partial x} \right) \left[\left(\rho_p c_p + \rho_w c_w z \right) T \right] = -\nabla \cdot \mathbf{q} \qquad \{5\}$$

Simple order of magnitude analysis shows that even at very slow machine speeds (U≈1 m/s) the machine direction transport of both heat and moisture is dominated by convection. Thus, as the diffusion is neglected in the machine direction, the above equations can be rewritten as

$$\rho_p \left(\frac{\partial z}{\partial t} + U \frac{\partial z}{\partial x} \right) = -\frac{\partial J}{\partial y} \qquad \{6\}$$

$$\left(\frac{\partial}{\partial t} + U \frac{\partial}{\partial x} \right) \left[\left(\rho_p c_p + \rho_w c_w z \right) T \right] = -\frac{\partial q}{\partial y} \qquad \{7\}$$

The moisture flux in the thickness direction contains both the effects of the diffusion of water vapor and the capillary flow of liquid water:

$$J = J_v + J_w \qquad \{8\}$$

The diffusive flux of the water vapor is modeled using [0]:

$$J_v = \frac{\varepsilon \psi D}{R_v T} \frac{p_{tot}}{p_{tot} - p_v} \frac{dp_v}{dy} \qquad \{9\}$$

where the effect of vapor diffusion resistance is given by

$$\varepsilon \psi = \begin{cases} 0 & \text{for } z \le 0.017 \\ 0.624 z^{0.575} - 0.06 & \text{for } z > 0.017 \end{cases} \qquad \{10\}$$

The partial pressure of water vapor is given by

$$p_v = p_{sat}(T)\varphi(T,z) \qquad \{11\}$$

where the effect of sorption is taken into account with the following correlation [0]:

$$\varphi = 1 - e^{-\left(47.58 \cdot z^{1.887} + 0.10085 \cdot (T-273.15) \cdot z^{1.0585}\right)} \qquad \{12\}$$

where the temperature T is expressed in the units of Kelvin.

The capillary flow of free water is modeled using the suggestion by Krisher and Kast [0 , 0]:

$$J_w = \rho_p \kappa \frac{dz}{dy} \qquad \{13\}$$

where the moisture diffusivity κ [m^2/s] is a function of temperature T [K] and the moisture ratio z [-]:

$$\kappa = \left(0.625 + 0.016 \cdot (T - 273.15)\right) \cdot \left(4.603E - 10 \cdot e^{3.178 \cdot z} + 7.475E - 11\right) \qquad \{14\}$$

On the right hand side of the energy balance in equation {7} the heat flux q contains the sensible heat transfer by thermal conduction in the paper web and the flow of enthalpy with the liquid water and water vapor:

$$q = -\lambda \frac{dT}{dy} + j_v h_v + j_w h_w \qquad \{15\}$$

Solution Procedure

It is seen that the set of partial differential equations {6} – {7} for z and T is nonlinear. This is even clearer after the substitution of equations {8} – {15} into them. The nonlinearity causes some challenges for the solution procedure to be accurate and stable. In the present paper, the finite difference method in its implicit form is used for the discretization. The grid and the nomenclature used are shown in Figure 2.

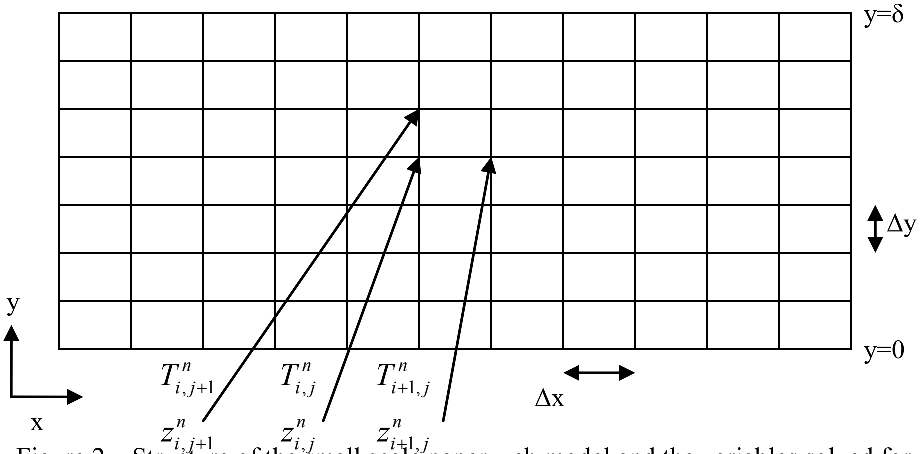

Figure 2 – Structure of the small scale paper web model and the variables solved for.

The time derivative is discretized using the first order approximation:

$$\frac{\partial z}{\partial t} = \frac{z^{n+1}_{i,j} - z^{n}_{i,j}}{\Delta t} \tag{16}$$

In all the other terms, the values at the future time step n+1 are used. In other words, the implicit method is used. Using the explicit forward-difference method, i.e. evaluating the values at the current time step n would be computationally simpler. However, this poses great challenges for the stability of the algorithm.

It is well-known, that the stability of the explicit forward-difference solution of the conduction equation is determined by the magnitude of the Fourier number, which is essentially a non-dimensional time step magnitude [0]. However, in the present nonlinear case it is not possible to determine analytically how long time steps can be taken to ensure stability. This makes the unconditionally stable implicit finite difference method the superior choice.

The x-derivative in the MD direction is discretized using the first-order upwind scheme [0]. This is the preferred choice due to the convective nature of the first order derivative.

$$\frac{\partial z}{\partial x} = \frac{z^{n+1}_{i,j} - z^{n+1}_{i-1,j}}{\Delta x} \tag{17}$$

On the other hand, the derivatives in the thickness (y) direction are diffusive in the nature. In this case, the central difference scheme brings higher accuracy:

$$\frac{\partial J}{\partial y} = \frac{J^{n+1}_{i+1/2,j} - J^{n+1}_{i-1/2,j}}{\Delta y} \tag{18}$$

$$\left(\frac{\partial z}{\partial y}\right)_{i,j+1/2}^{n+1} = \frac{z_{i,j+1}^{n+1} - z_{i,j}^{n+1}}{\Delta y} \qquad \{19\}$$

The substitution of the discretized derivatives in equations {16} – {19} into the continuum equations {6} – {15} forms a set of nonlinear algebraic equations for the temperature T and the moisture ratio z at each grid node:

$$z_{i,j}^{n+1} = \left(\frac{1}{\Delta t} + \frac{U}{\Delta x}\right)^{-1}\left(\frac{z_{i,j}^{n}}{\Delta t} + \frac{Uz_{i-1,j}^{n+1}}{\Delta x} - \frac{J_{i,j+1/2}^{n+1} - J_{i,j-1/2}^{n+1}}{\Delta y}\right) \qquad \{20\}$$

$$\begin{aligned} T_{i,j}^{n+1} &= \left(\frac{1}{\Delta t} + \frac{U}{\Delta x}\right)^{-1} \\ &\left(\frac{T_{i,j}^{n}}{\Delta t} + \left(\rho_p c_p + z_{i,j}^{n+1}\rho_w c_w\right)^{-1}\left[\left(\rho_p c_p + z_{i-1,j}^{n+1}\rho_w c_w\right)\frac{UT_{i-1,j}^{n+1}}{\Delta x} - \frac{q_{i,j+1/2}^{n+1} - q_{i,j-1/2}^{n+1}}{\Delta y}\right]\right) \end{aligned} \qquad \{21\}$$

It is seen that equations {20} – {21} are implicit, since the fluxes q and J on the right hand side of the equations depend on the moisture z and the temperature T at the future time step. However, a significant advantage in the equations is that information only travels downstream in the MD. This makes the solution of the set of equations rather efficient, despite the nonlinearities.

The solution procedure is as follows:

1. Obtain the fluxes J and q at the surfaces of the paper web from the large scale CFD simulation as boundary conditions.
2. Begin with i=1 (the values at i=0 are known as a boundary condition)
3. First approximate the unknown values at the future time step with the previous time step values: $z_{i,j}^{n+1} \approx z_{i,j}^{n}$, $T_{i,j}^{n+1} \approx T_{i,j}^{n}$
4. For each j, compute the new fluxes J and q inside the paper web using the equations {8} – {15} and the discretization given by equation {19}.
5. Solve the equations {20} – {21} sequentially for each j in order to obtain updated estimates for $z_{i,j}^{n+1}$ and $T_{i,j}^{n+1}$. Apply under-relaxation for maintaining stability.
6. Repeat steps 4 and 5 until a converged solution is obtained.
7. Proceed one step downstream in the MD to treat the grid points at i+1 and repeat steps 3 – 6 until new values for $z_{i,j}^{n+1}$ and $T_{i,j}^{n+1}$ are found for each i and j.
8. Pass the values of temperature T and the moisture ratio z for the large scale CFD model to be used for determining boundary conditions.
9. Advance to time step n+1 and perform the large scale CFD simulation.

RESULTS

In order to illustrate the usability of the model, a numerical example was solved. In the example a straight paper web was modeled for a length of 2 meters in an idealized open draw. The paper web of thickness δ=1e-4 m was traveling with the machine speed U=30 m/s.

As the upstream boundary condition at x=0, moisture ratio of z=0.5 was used. The moisture ratio was initially uniform in the thickness direction. The upstream temperature varied linearly in the thickness direction from 352.15 K (bottom side) to 343.15 K (top side).

In the CFD simulations, only free boundaries were used in addition to the moving paper web. The inlet temperature at the free boundaries was 343.15 K and the humidity ratio was $\omega=0.08$ $kg_{H2O}/kg_{dry\ air}$.

In the first stage, the steady-state results were obtained with the algorithm described in the previous sections. The steady-state solution was obtained using the transient formulation by continuing the simulation until there were no changes in the variables.

The humidity ratio in the surrounding air is shown in Figure 3. It is seen that the water vapor boundary layer increases in the MD direction.

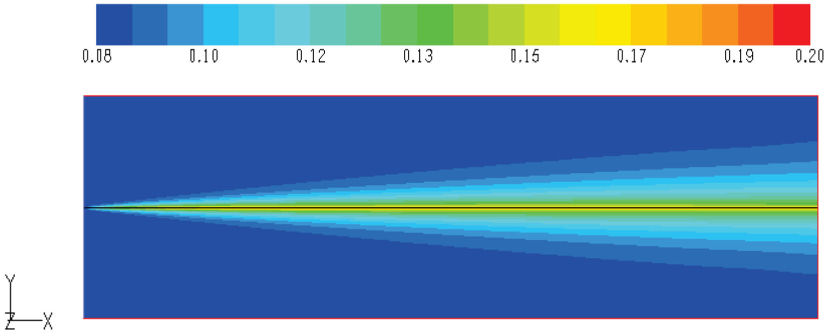

Figure 3 – Steady-state humidity ratio of air ω ($kg_{H2O}/kg_{dry\ air}$) in the CFD model.

The temperature of the surrounding air is plotted in Figure 4 as a function of the y-coordinate for different values of the MD-coordinate. It is seen that for small x, the warm paper web transfers heat into the surrounding air. However, the surface of the paper web cools down in the MD-direction due to the energy losses caused by sensible heat transfer and evaporation. Thus, eventually the paper web becomes cooler than the surrounding air. It is seen in Figure 4 that the temperature field remains non-symmetrical even in the downstream due to the upstream boundary condition.

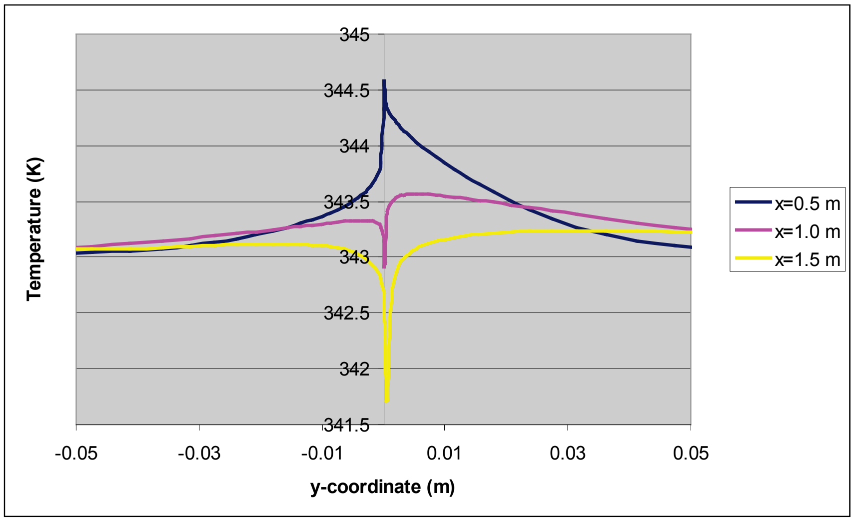

Figure 4 – Steady-state air temperature (K) in the CFD model as a function of the y-coordinate for different values of the MD-coordinate.

The moisture ratio z and the temperature T in the paper web are shown in Figures 5 – 6. It is seen that in the upstream the bottom of the paper is much warmer than the top. However, at about x=0.4 m, the temperature profile is already almost symmetrical. This happens due to internal heat transfer within the paper web but also because the warm surface of the paper loses more energy due to the higher evaporation rate.

It is seen that the moisture ratio profile in the paper web becomes non-symmetrical even though the upstream boundary condition is a uniform moisture ratio. This happens from the same reason: the warm bottom surface naturally evaporates more than the cool top surface of the web.

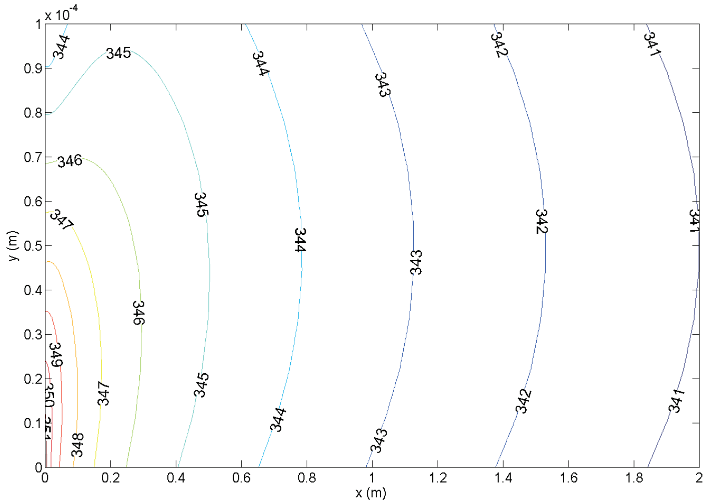

Figure 5 – Steady-state paper web temperature (K) in the small scale model.

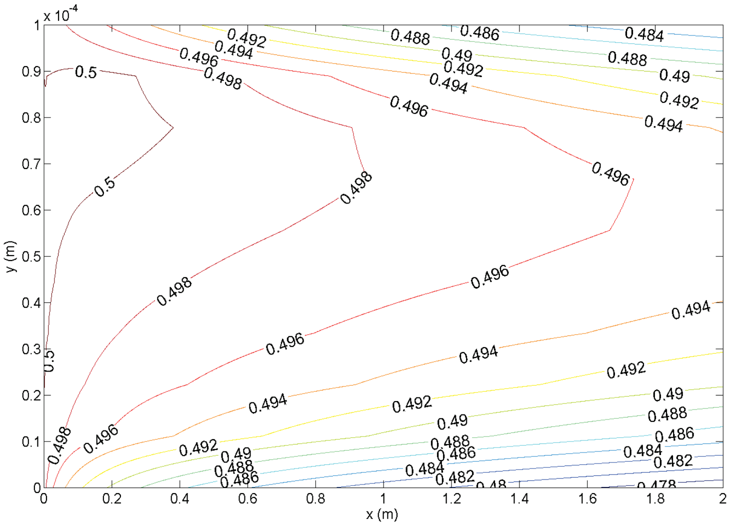

Figure 6 – Steady-state paper web moisture ratio z (kg_{H2O}/kg_{dry}) in the small scale model.

In order to illustrate the full transient operation of the model, a step change in the upstream boundary condition was made. At time t=0, the upstream moisture ratio was abruptly changed from the value z=0.5 to the value z=0.45. It is seen that the frontier travels through the domain at the velocity determined by the machine speed U. However, the frontier of the moisture ratio is not extremely sharp. The frontier becomes smoother due to the interaction with the surrounding air.

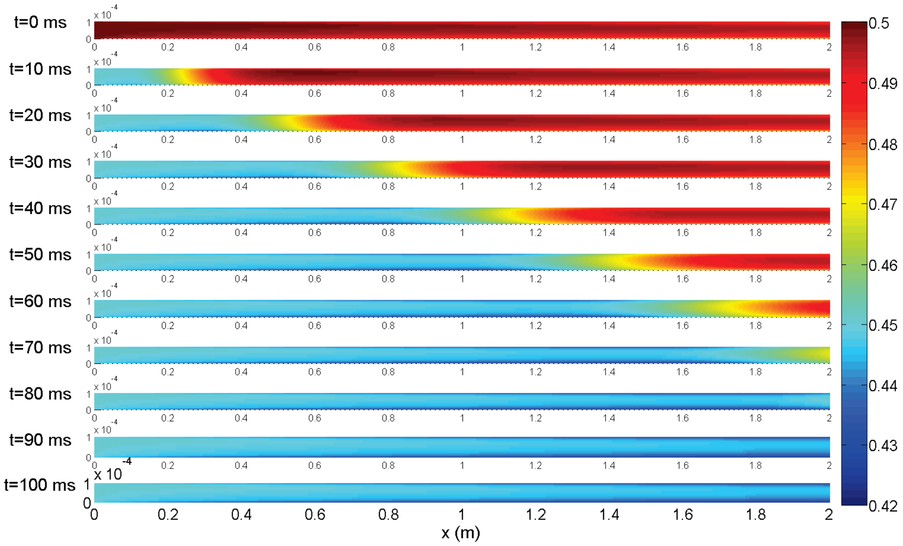

Figure 7 – Transient paper web moisture ratio z (kg_{H2O}/kg_{dry}) in the small scale model.

CONCLUSIONS

In the present paper, a paper web drying model was described. The model consists of two parts: the large scale CFD model and the small scale paper web model. What makes the model novel is that it is transient and that the transport phenomena in the thickness direction are taken into account in the small scale model.

The ability to take into account the transport phenomena in the thickness direction of the paper web together with the large scale air flow analysis is important when using the simulations for predicting dryer section drying performance or issues affecting paper quality.

The present model can be used for different applications. The present paper has only shown a simple example, but naturally the computational domain can contain heated rolls, vacuum rolls, grooved rolls [0] and the dryer fabric [0].

Moreover, the ultimate goal is to combine the present model with a fluid structure interaction (FSI) model, which predicts the deflections of the paper web and the dryer fabric [0]. For achieving this goal it is important that the present model is formulated as transient, because the web deflections and flutter are often transient in nature.

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Name & Affiliation	**Question**
Volker Traudt, Inometa Inc.	Regarding your model that analyzes heat and humidity transfer into and out of the sheet: Are you differentiating the different heat transfer paths like radiation versus convection versus conductive heat transfer?
Name & Affiliation	**Answer**
Fredrick Bergström, Process Flow Ltd Oy	Yes we accommodate this in the program. We adjust the surface temperature for the paper and some boundary condition for the CFD software that will calculate heat transfer, even radiation if you choose. Depending on the air flow, we can enhance every detail of energy transfer at the surface of paper. If you have hot air blowing on the surface it will be also solved. It will depend on the geometry. There is no assumption for the alpha value used at the surface.
Name & Affiliation	**Question**
Stephen Lange, Procter & Gamble	How many processors are you using for this solution? How long does it take to make the model run?
Name & Affiliation	**Answer**
Fredrick Bergström, Process Flow Ltd Oy	Typically one processor is used. The solution may require a day depending on model size. The example I showed only required a few minutes. With the geometry of a paper machine, the solution can be computed overnight.

DISCUSSION II

Leaders: **S. Lange,** Procter & Gamble, and **P. Pagilla**, Oklahoma State University, USA

Name & Affiliation	**Comment**
Steve Lange, Procter & Gamble	I attended Session 3. There were a couple of presentations on roller design. One was on use of microgrooves to improve web/roller traction while recognizing increased traction can cause wrinkling. The second paper on roller design focused on carbon fiber rollers and their damping properties. There were two papers demonstrating the use of computational fluid dynamics for predicting moisture transport in webs or fluid/structure interaction. There was an interesting paper on use of Moire fringe patterns for characterizing out-of-plane displacements of webs. There was a paper that described the effect of nips on paper properties, like gloss and smoothness, and paper sheets, and another paper that described how a nip can actually cause sliding of the sheets to achieve a separation. There was a very interesting paper on predicting laminate curl in multiple directions.
Name & Affiliation	**Comment**
P. R. Pagilla, Oklahoma State University	Let me summarize Session 2. There was an overview and three topics. Dan Carlson talked about how we can use advanced controllers in web handling and what are the benefits and limitations of using advanced controllers and what do we need to do to transition from the current PID controllers to advanced controllers. Three main topics were covered in the other 7 papers. The first was accumulators. Neal Michal talked about his observations on the data he collected on his line. John Shelton discussed improving web accumulators design using dynamic models and control of the accumulators. The second topic was the modeling of tension and validation. Carlo Branca discussed how you refine models to include oscillations that you find in recorded data in experiments. There was a paper from Ming Yang from Xerox on a dynamic model on high precision web belt transport systems. Then there were two papers discussing resonant frequencies and self-excited systems. One was presented by Dave Roisum. I talked about low parameter models for predicting resonant frequencies and how to use them.
Name & Affiliation	**Question**
P. R. Pagilla, Oklahoma State University	How do you define a self-excited system? How do I know it is self-excited as opposed to resonant excitation?
Name & Affiliation	**Answer**
Dave Roisum, Finishing Technologies, Inc.	Resonance occurs at certain conditions and it is usually confined at 2-10 times magnification depending on damping. It is self-limited.

Name & Affiliation	**Question**
Neal Michal, Kimberly-Clark	With regard to the natural frequency for a roller, obviously the mounting stiffness for the roller is important. If the roller is mounted, will a bump test of the system provide accurate results or is there something that we risk missing to analyze a potential critical frequency?
Name & Affiliation	**Answer**
Dan Perdue, Goss International	I would say that is the easiest way. It is a simple way to verify or determine the stiffness of the structure.
Name & Affiliation	**Comment**
Dave Roisum, Finishing Technologies, Inc.	I will add to that. You need to have a good idea of what the roll shapes are so that you can strike it in the right direction and place. Otherwise, you may not excite the modes of interest. In the paper industry, we sometimes excite everything by simply dropping a very heavy 100,000 pound reel on the foundation. That usually excites everything. You have to hit it really hard to excite all the modes.
Name & Affiliation	**Comment**
Bob Lucas, Winder Science	Earlier we were discussing self-exciting systems. We should recognize there are some things that are self-exciting and there are elements of the machine that have negative damping, which is different. If you take a web support roll and you input an impulse, it is going to vibrate at some natural frequency or one of many natural frequencies. A rotating imbalanced roll has negative damping. The imbalance force increases with mass eccentricity and nonlinearly with angular velocity. A perfect example of this is a core. When a wound roll expires at a high speed on a wide printing press the core will approach its first natural frequency. A runaway situation will occur where the eccentricity amplitude keeps growing until the core self destructs. This is a perfect example of negative damping characteristic.
Name & Affiliation	**Question**
Neal Michal, Kimberly-Clark Corporation	What if you do not have a 25 ton weight that you can drop on the floor, how many times do you have to hit a roller and in what directions? Do you hit them on the corner points, 3 planes or what?
Name & Affiliation	**Answer**
Dave Roisum, Finishing Technologies, Inc.	You really have to know what to expect for the problem natural frequencies. On high speed equipment, trying to avoid natural frequencies is like trying to avoid bugs hitting the grill of your car, it’s not possible. You must know something about the modes that cause a problem and you strike the structure in such a way that you excite that mode. With sensitive equipment, you usually don’t have to hit it very hard. But this requires you know where to hit it.
Name & Affiliation	**Answer**
Dan Perdue, Goss International	You can input impulses at several locations across the width of a roller. It is very easy to do these measurements and see where you get significant response. It is unlikely

	that I will miss a natural frequency with multiple hits. If I strike at a node, I won't excite the structure. But if I hit just off the node, I will excite the structure. This is the general strategy, just sample at several locations and get quick and easy measurements.
Name & Affiliation	**Question**
Bob Lucas, Winder Science	If you are striking a roll, do so at the center of the machine and you will probably excite its first mode. If you strike it closer to the supports, then you are going to excite higher modes of vibration. If you are trying to excite a structural beam, such as a rider roll beam on a winder, you can generate a lot of confusion if you don't pay attention where you strike it. It is best to strike it where there is a reinforcing gusset, so you do not measure high frequency modes you are probably not interested in.
Name & Affiliation	**Question**
Mark Weaver, Rockwell Automation	Speaking as a representative of a drive manufacturer, we tend to avoid feeding energy into self-exciting systems. We witness self excitation most frequently in torsional modes. We have several design rules for the torsional stiffness to avoid these resonances. Machines can be destroyed by these torsional modes. Is there any way we could avoid self-excited lateral mode vibrations?
Name & Affiliation	**Answer**
Dave Roisum, Finishing Technologies, Inc.	These are not self-exciting systems. These are mere resonances. Self-exciting systems can be recognized because the resonance will increase in magnitude until something fails.
Name & Affiliation	**Comment**
Mark Weaver, Rockwell Automation	This can be done with drives. I guess your point is that it has a chaotic element to it. In other words, there is a catastrophic event and it reinforces and propagates, such as an avalanche.
Name & Affiliation	**Answer**
Dave Roisum, Finishing Technologies, Inc.	The avalanche is a good analogy because the avalanche comes from mass. If the moving mass entrains more mass it is an example of how the event is propagating or self-exciting. There are not many self-exciting systems in web handling. When you see them, you will recognize them.
Name & Affiliation	**Question**
Steve Lange, Procter & Gamble	I want to change the discussion a bit to cover subjects from the other session. I process a lot of porous webs, so air entrainment is not an issue for most of my webs. I have seen several papers on air entrainment. Today there was one that studied very small groves, only .2 mm deep, but data was shown that proved the grooving was effective. I saw a paper yesterday where the grooves were 25 mm deep – extremely deep. What is your experience? Why would one work and one not? What is your understanding of how groove rollers function and what would dictate the scale of the grooves, including the pitch, depth, and shape?

Name & Affiliation	**Answer**
Bob Lucas, Winder Science	I believe that a lot depends on the type of problem you are trying to solve and what arena you are working in. Whether you are working with plastic films travelling at 150 fpm or webs of paper travelling 10,000 fpm makes a difference. From my experience, deeper grooves provide more air handling capacity and greater negative pressure is developed which provides increased traction. It was very interesting to see the presentation earlier that showed grooves that were very, very deep demonstrated that a significant negative pressure developed. In some of my tests covered up the grooves with masking tape. We later found when we removed the masking tape that dust had collected on the underside of the tape. We knew there was some high velocity air travelling through the grooves. With increasing velocity there will be a point where the air capacity of a groove gets saturated and it cannot accommodate more air. I know we've had winders that are running at 10,000 fpm and we can see the web lifting off the drums because our grooves were not deep enough. For films that are travelling at low speeds, a 0.5 mm deep groove may be all that is needed. But if velocity is increased this depth groove would be found inadequate.
Name & Affiliation	**Question**
Steve Lange, Procter & Gamble	What is the mitigating case, why would you not always make the grooves extremely deep?
Name & Affiliation	**Answer**
Bob Lucas, Winder Science	I believe it is economics. You buy a machine that is appropriate for a particular web. In our case, we encountered a practical limit because our lathe parting tool could not cut a groove deep enough. Maybe we could have cut deeper grooves had we spent more time and effort on the practical issues of the machining.
Name & Affiliation	**Comment**
Dave Roisum, Finishing Technologies, Inc.	In the mechanics of rollers book, I proposed a recipe to size grooves. It basically calculates the amount of air entrained and then sizes the grooves large enough to accommodate that air. That was a first attempt to try to give people guidance on how to size grooves. Ron Swanson checked that and it turned out to be quite a decent recipe to get you close to the size of grooves for any nonporous application.
Name & Affiliation	**Question**
Steve Lange, Procter & Gamble	What is the heuristic for that?
Name & Affiliation	**Answer**
Dave Roisum, Finishing Technologies, Inc.	You design the grooves or the roller roughness to handle the volume of entrained air. You size the groove width to minimize wrinkling problems, I give a guideline of no more than 10 times the thickness. Otherwise you could get wrinkles from the grooves. This could be avoided by cutting the grooves with a helical angle. The grooves

	cannot be too wide or you get wrinkles. They cannot be too narrow because it's not economical for the manufacturer. That's the heuristic.
Name & Affiliation Tim Walker, T. J. Walker & Associates	**Comment** Just a couple of more comments on grooving and friction. Traction often gets talked about as a wonderful thing and it is because we like to be in lateral control of the web. One of the comments on Prof. Hashimoto's paper was that traction caused wrinkles – and that's not true. Traction by itself does not cause wrinkles. It's the enabler that holds the web wrinkle shape on the roller and causes stress. Many people find that a grooving pattern that provides moderate lubrication is what they want. You see gross diamond patterns with a pitch 2 inches apart. You know it's not doing a great job of anti-lubrication but provides enough traction that the rollers turn because they have decent bearings. If they don't have enough traction to make wrinkles but yet the rollers still turn and control the lateral motion of the web they have achieved an optimal design. I think it is wrong to look at this only from the perspective of designing the grooves to vent the entrained air.
Name & Affiliation Steve Lange, Procter & Gamble	**Answer** I think that is what I liked about Hashimoto's paper. The applied world of web handling is a trade off in many cases. There's not really one right answer. Even for the grooved roller, the web goes through a series of speeds through transient conditions, so there cannot be one groove design that is perfect for all that. You would need a variable groove to handle speed ranges.
Name & Affiliation Neal Michal, Kimberly-Clark	**Question** This question is for Dave Roisum. In you book *Mechanics of Rollers*, you have a table that gives acceptable deflection criteria to avoid wrinkles. Has there been more development in this area?
Name & Affiliation Dave Roisum, Finishing Technologies, Inc.	**Answer** The table was developed from the strictest guidelines used by mature machine builders. These guidelines are good enough for almost every application. It is possible that it could be too good.
Name & Affiliation Neal Michal, Kimberly Clark Corporation	**Question** In your book, you indicated practical experience is very important. My question was has there been some refinement of that table?
Name & Affiliation Dave Roisum, Finishing Technologies, Inc.	**Answer** Yes, but it is a somewhat small list. There have been losses based on that book for breach of contract for poor design.
Name & Affiliation Steve Lange, Procter & Gamble	**Question** What if you have 8-10 rollers on a moving carriage and they are all deflecting the same amount? Is it a linear function, is it a power function? Do you have more probability for wrinkles above and beyond the simple

	addition of additional idlers in series that are deflecting the same amount? This is the example of an accumulator where several rollers can deflect.
Name & Affiliation	**Answer**
Jerry Brown, Essex Systems	If you have a roller that is bowed because it is deflected or one that is concave you lose the spreading from the roller upstream. A series of deflecting rollers simply maintains the wrinkling tendency that developed at the first roller. In other words, it doesn't grow. It is not multiplicative or even additive.
Name & Affiliation	**Comment**
Tim Walker, T. J. Walker & Associates	A series of deflecting rollers will gather the web. In a gathering mode you have an additive effect; each roller gathers the web a little more. In a spreading case the elasticity of the web will cause the web to return to the un-stretched width. In the gathering mode the web will continue to gather until it buckles over itself. Finally the web will become a rope.
Name & Affiliation	**Comment**
Neal Michal, Kimberly-Clark Corporation	To complicate this, I showed a tensile profile earlier today for an accumulator where the exit tension was over 4 times higher than the entrance tension. So not only are the rollers deflecting, but they are increasing in deflection as you go from the entrance of the accumulator to the exit.
Name & Affiliation	**Comment**
Tim Walker, T. J. Walker & Associates	Neal, moving from low to high tension is not your problem. It's going from high to low tension where you are trying to get nip recovery and that is what creates your span expansion wrinkles.
Name & Affiliation	**Comment**
Neal Michal, Kimberly-Clark Corporation	We have seen situations where both increases and decreases in tension have caused wrinkles.
Name & Affiliation	**Comment**
Dave Roisum, Finishing Technologies, Inc.	Accumulators have another problem which is keeping alignment through the stroke. It is difficult to produce designs that keep the rollers aligned throughout the stroke range.
Name & Affiliation	**Comment**
Steve Lange, Procter & Gamble	This was the key issue, not roller deflection, on every accumulator I had a problem with. That is the real design difficulty that I've seen. Some systems use cables and all kinds of things that are horrible for trying to maintain alignment. Sometimes you can maintain alignment when the stroke is short but you cannot maintain it when the stroke becomes long. This is a key problem with those systems.
Name & Affiliation	**Question**
Jerry Brown, Essex Systems	Has anyone tried to make all the rollers slightly concave on accumulators?
Name & Affiliation	**Answer**
Steve Lange, Procter &	I have done it on part of the accumulator, on the fixed

Gamble	portion.
Name & Affiliation	**Question**
Jerry Brown, Essex Systems	Did it help?
Name & Affiliation	**Answer**
Steve Lange, Procter & Gamble	Yes.
Name & Affiliation	**Comment**
Dave Roisum, Essex Systems	There can be a disadvantage because the least amount of mis-tracking will be amplified as the web moves through the accumulator. You will see the web progressively track to the left or right as it passes through the accumulator.
Name & Affiliation	**Answer**
Steve Lange, Procter & Gamble	That is true but if the concave profiles are small that is not a big effect and it can be calculated.
Name & Affiliation	**Comment**
Dave Roisum, Essex Systems	Karl Reid suggested an interesting idea: What about precision ball screws? There are very few mechanical devices that are good enough to hold alignment through that stroke but there are precision ball screws for the tooling industry that might be a possibility.
Name & Affiliation	**Comment**
Jamie Lynch, Armstrong World Industries	We have had accumulators that used ball screws for 30-40 years. We control position of the accumulator by controlling velocity and then trim with tension. But we have used ball screws on at least the four corners of the accumulator. Sometimes we use six ball screws, four on the corners plus two in the middle. This works well.
Name & Affiliation	**Comment**
Mark Weaver, Rockwell Automation	You can also employ multiple linear motion axes and you can maintain level within a few thousandths. So it becomes a question of calibration and predictability. You can get very precise motion. It is expensive, no question about it. It sells more drives.
Name & Affiliation	**Comment**
Jamie Lynch, Armstrong World Industries	Our ball screws are all tied together with drive shafts. One motor powers all shafts.
Name & Affiliation	**Question**
Neal Michal, Kimberly-Clark Corporation	I have a question for Mark Weaver. Your paper on modern controls was excellent. I know you said that a number of advanced control methods are being reviewed. Does one appear to be the leading contender? If so, how do we commercialize that? How do we get that to the plant floor? Currently PID control is so well understood, how do we made that leap to the more advanced control methods?
Name & Affiliation	**Answer**
Mark Weaver, Rockwell Automation	We know we cannot be all things to all people when it comes to the outer loop controls in particular proprietary algorithms. We provide a user programmable space inside the drive processor for that purpose. It is possible for someone to develop a proprietary or a public application

that would run at the processor rate inside the drive, very close to the process that you are trying to control. In this environment you could develop add-on instructions that would allow you to develop an algorithm that would have specified the inputs and outputs. You could develop the various help files and a complete platform. The alternative would be that we as a drive manufacturer would have to develop, support and maintain it. At some point the drive manufacturer has to decide what is economically best for the company. I have trouble sometimes convincing our company that this is worth doing. In many cases a partner will support us in these activities. We may partner with a company that develops an algorithm and then we can sell it as an add-on to our software. I'm not going to say that Rockwell is going to develop a web handling specific controller but we would probably be interested in partnering with people that develop advanced controls.

Name & Affiliation	**Comment**
P. R. Pagilla, Oklahoma State University	I've had some experience with implementing controllers. There is a level of complexity. You have to understand what the algorithm is doing. Dan Carlson supports building hooks that you can add on to existing controllers and improve the performance. I believe the easiest way to transition to an advanced controller is probably using an adaptive algorithm. You can develop an adaptive algorithm for one part of the process – maybe an unwind, rewind, or one of the process sections. That is possible because we have models that are reasonably well developed for these sections. We can develop what is called model reference adaptive controls where you mimic the models that you have with the reference model. That's possible. That is probably the first thing to do when you implement an advanced control.
Name & Affiliation	**Question**
Karl Reid, Oklahoma State University	David Roisum made a comment about accumulators that I didn't understand in the earlier session. Type 1, Type 2, do away with it. Can you explain that?
Name & Affiliation	**Answer**
David Roisum, Finishing Technologies, Inc.	A Type 1 error is belief something is significant when it is not. A Type 2 error is belief something is not significant when it is. Clearly the accumulator is significant, so we have passed those. Perhaps we should look in new directions whenever possible because the problems with these types of machine components are many and severe.
Name & Affiliation	**Comment**
Tim Walker, T. J. Walker & Associates	A lot of web handling problems would be solved if we get rid of accumulators, winders, and nip rollers.
Name & Affiliation	**Question**
Ron Lynch, Procter & Gamble	In Session 2 there was a lot of discussion dealing with the imperfections from span length variations from out-of-round rolls, dealing with resonant frequencies, and various

	things that excite the system that drive it away from normal behavior. It does seem that these things are more important to some people based on the papers here. Are there any thoughts on that?
Name & Affiliation	**Comment**
Steve Lange, Procter & Gamble	Another way stating this is where do you spend your time on your problems? Are they in these areas or are they in more conventional areas of web handling?
Name & Affiliation	**Answer**
Ron Lynch, Procter & Gamble	Historically, the center here has dealt with understanding the behavior of ideal webs under ideal conditions. More and more the interest is moving toward understanding the behavior of non-ideal materials on non-ideal machines.
Name & Affiliation	**Question**
Steve Lange, Procter & Gamble	Another observation is the prevalence of computer simulation. Both CFD and FEM modeling is becoming more prevalent in these presentations. Also, the drop in cost of imaging, cameras, etc., seems to be driving the use of more of those tools. Even in smaller companies these simulation tools are becoming more affordable. Are they affordable enough for you to start using them? I am asking this mainly because the center here does some of those kinds of simulations, but shies away from them in some cases because the sponsors don't always have the resources to employ that kind of modeling. I am trying to get a sense of from the group of where you see it within your own companies.
Name & Affiliation	**Answer**
Dave Roisum, Finishing Technologies, Inc.	I used to be a modeler for several years so I can speak from experience. I have also worked with a large company that had a department of modelers. I can tell you the cost is severe and it's not the software. The cost is that you must dedicate most of your duty to becoming proficient with these extremely complicated tools. What is even more remiss now is the temptation to believe that what you get out of the computer without the requisite checking in the field. When I learned finite element programming, I had a month of tutelage with an experienced modeler. He gave me a simple task – to model a card table with a person sitting on the corner. When I got the model finished he asked me "How do you know that the results from your model are correct?" This was just the static part of linear analysis and he showed me how to check this. Without knowing how to check the work it becomes dangerous.
Name & Affiliation	**Comment**
Steve Lange, Procter & Gamble	The counter argument is that it's not cheap to run an experiment either. That is what we are finding as well. We invest millions in these machines and they are there to make product, not necessarily to learn on. There must be a balance between modeling and testing. There are things that can be learned in models that cannot be learned in the real

	world.
Name & Affiliation	**Comment**
Dave Roisum, Finishing Technologies, Inc.	You have to model problems that are economically appropriate. For example, I was asked to size foundations for a big heavy machine. It turned out you could either spend $50,000 in analysis or you could buy $50,000 of concrete which would ensure a sufficient foundation. That is how many industries work. Analysis is required in optimal designs such as in aircraft design. In many industries economics may dictate that you over-design, because you can't afford the analysis.
Name & Affiliation	**Question**
Neal Michal, Kimberly-Clark Corporation	This question is regarding air entrainment: Does anyone know if a smooth paper web would have more or less air entrainment at the same speed as a porous web? This is in reference to a free span not at the roll.
Name & Affiliation	**Answer**
Bob Lucas, Winder Science	I have been around a lot of high speed machinery. I would say that rough paper entrains more air. A number 1 premium gloss coated paper may air float at 50 feet a minute. When you witness equipment that is moving at high speed and you can feel the air that is being pulled along with a rougher grade, like a liner board grade. There is quite a difference.
Name & Affiliation	**Comment**
Neal Michal, Kimberly-Clark Corporation	At the speeds we run, my observation is we are moving more air than web mass.
Name & Affiliation	**Comment**
Tim Walker, T. J. Walker & Associates	I don't see how you can move a mass of air greater than your web mass. It is good to differentiate the dry air drag with zero lubrication. You are talking about air drag acting on the web and how much web tension is dissipated by air drag. Surface roughness does affect drag.
Name & Affiliation	**Comment**
Dave Roisum, Finishing Technologies, Inc.	A nonwoven is a thick surface moving through a large volume of air. For rollers the amount of air drag is almost negligible even at extremely high speeds. This may not be the case for nonwovens because there is so much surface area compared to a roller and nonwovens are transported at low tensions. It could be significant.