# Characterization of Absorbent Flow Rate in Towel and Tissue

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**ABSTRACT**

The quality of a paper towel is often judged based on how quickly it can wipe up a spill. However, the test methods currently available cannot repeatably measure significant differences in absorbent rate between samples. Recent round-robin testing evaluations by TAPPI and CEN organizations have shown that past methods, such as ASTM D5802-95 and TAPPI T561-pm [1], are unreliable due to high variability. The reasons for the lack of repeatability are unclear. The relation between the wicking mechanism and the fundamental absorbent properties needs to be better understood. This paper uses x-ray imaging to show the overall flow characteristics of fluid absorption within a towel, and compares the results to model predictions to show which parameters are important to the process. From this understanding, a revised test method is proposed that provides adequate statistical discernment of absorbent rate properties of tissue on a simple lab-bench scale device.

**INTRODUCTION**

Tissue and towel products offer an inexpensive and convenient means to pick up a liquid spill and dispose of it. Such products can generally pick up between five and ten times their weight in liquid and hold it without dripping. Tissue accomplishes this remarkable feat by arranging, small (~10 um wide by 1-3 mm long), hydrophilic (<50 degree contact angle) fibers in a low density structure (porosity > 0.9). These fibers give a tremendous surface area per unit volume to hold the fluid (typically > 0.6 $m^2/cm^3$). The ability of tissue to absorb a fluid quickly depends upon having a high capillary pressure to be able to suck the liquid in yet also high permeability to allow the fluid to quickly flow away from the point of insult. The quality of the fibers and the care with which they are laid down and dried can have significant effects on the absorbent rate.

Measuring rate of absorption in tissue paper is dependent on many experimental conditions that are often poorly controlled in existing techniques, such as tissue sample size, head level, number of plies, effect of interfaces, and position of the sample with respect to gravity (vertical vs. horizontal wicking). How these parameters are accounted for in technique can strongly affect the measured value and even the relative rankings of different tissues. Before defining a method to measure absorbent rate, it is useful to understand the end use of tissue and towel products in order to match the test methodology to the end-use performance.

Tissue paper is primarily used to wipe liquids and solids off of a solid surface, whether it is hard such as a floor or soft such as skin. Thus, the purpose of tissue is to absorb the liquid and solids and remove them from a surface. In this light, this paper will focus on measuring absorbent properties of tissue against a surface. The focus is only on the liquid absorbency, and not the cleaning and solid removal. Furthermore, when wiping a spill, the point of insult is typically in or near the center or the sheet, far from the edge. The absorbent action pulls the fluid away radially from the point of insult. Therefore a good test should be able to evaluate the radial wicking capability of a sheet in contact with a surface.

It has been shown elsewhere that radial wicking can be related to linear wicking analytically [2] and in experiments with thin filter papers with a well defined thickness [3]. Here we will show that linear wicking measured by x-ray densitometry can be related to much simpler radial wicking experiments

even for thick absorbent towels with less well defined thicknesses.

Absorbency in an idealized horizontal porous material is characterized in one-dimension by the Washburn equation [4].

$$L^2 = \frac{\gamma d\, t}{4\mu} \tag{1}$$

$L$ is the distance a liquid has traveled in time $t$, $\gamma$ is the surface tension of the liquid, $d$ is the pore diameter, and $\mu$ is the liquid viscosity. This can be re-written in terms of the mass (M) of fluid absorbed, the permeability, $K$, and driving pressure $\Delta P$:

$$M = \rho \cdot T \cdot W \sqrt{\frac{2K\,\Delta P}{\mu}} \sqrt{t} \tag{2}$$

*T* and *W* are the thickness and width of the porous material and ρ is the liquid density, and the relationship of fluid absorbed vs. time is a square-root relationship for a one-dimensional linear flow.

For a radial flow, similar relationships have been developed [5] and tested experimentally [2, 3]. For completeness, here we re-derive the radial wicking equation for a general porous medium with permeability K, and a thickness T. Darcy's law for radial flow is given by:

$$Q = \frac{2\pi K T}{\mu} r \frac{dP}{dr} \tag{3}$$

where $Q$ is flow rate, $\mu$ is the fluid viscosity, $r$ is the radial location in the disk, and $P$ is the pressure. For fully saturated flow, $Q$ is constant with respect to $r$ due to conservation of mass, so we can integrate to obtain:

$$Q = \frac{2\pi K T}{\mu} \frac{(P_f - P_i)}{\ln\left(R_f / R_i\right)} \tag{4}$$

where the subscript *f* refers to the fluid front and *i* refers to the fluid inlet. $R_i$ is the radius of the fluid inlet at the center of the flow field. As the fluid flows into the disk, the fluid front moves outward and $R_f$ grows. Assuming a blunt fluid front (i.e. that the porous medium is dry in front of the front and fully saturated behind the front) we can relate the location of the fluid front to the flow rate using:

$$Q = \frac{d\left(\pi T\left(R_f^{\,2} - R_i^{\,2}\right)\right)}{dt} = 2\pi T R_f \frac{dR_f}{dt} \tag{5}$$

Combining expressions (4) and (5) we obtain:

$$R_f \frac{dR_f}{dt} = \frac{K}{\mu} \frac{\Delta P}{\ln\left(R_f / R_i\right)} \tag{6}$$

This can be integrated as:

$$\int R_f \ln\left(R_f / R_i\right) dR_f = \int \frac{K}{\mu} \Delta P dt \tag{7}$$

to find:

$$R_f^{\,2}\left(\ln\frac{R_f}{R_i} - \frac{1}{2}\right) + C = \frac{2K\,\Delta P}{\mu} t \tag{8}$$

With $R_f = R_i$ at time t=0, the constant of integration is $C = R_i^2/2$. Eq. (8) can be recast in terms of mass using $M = \pi \rho T(R_f^2 - R_i^2)$ to get:

$$\left(\frac{M}{\pi\rho T} + R_i^{\,2}\right)\ln\left(\frac{M}{\pi\rho T R_i^{\,2}} + 1\right) - \frac{M}{\pi\rho T} = \frac{4K\,\Delta P}{\mu} t \tag{9}$$

This assumes fully saturated media and no external driving pressure gradient.

Eq. (9) cannot be easily inverted to give *M* as a function of time, but it can be easily graphed. *Figure 1* shows a plot of mass vs. time for $R_i$=1mm, $T$=1mm, $4K\Delta P/\mu$=1000mm$^2$/sec. For small values of $4K\Delta Pt/\mu$, the mass increases as ~$t^{0.5}$, but at large time the mass vs. time power relationship approaches unity.

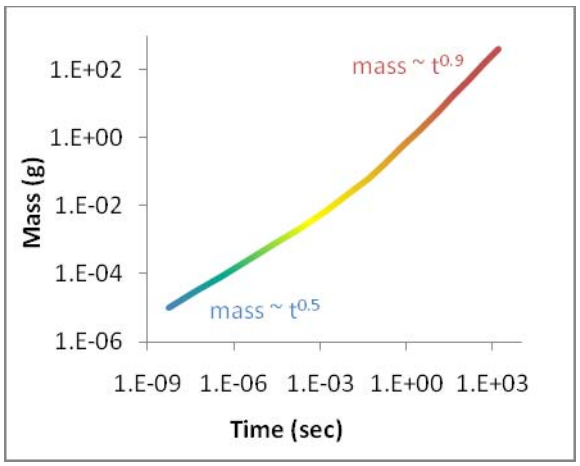


FIGURE 1 Radial power law dependence of mass flow vs. time

The relationship between mass and time is no longer a simple $t^{0.5}$ power law as in the one-dimensional linear case, but a logarithmic relationship that results in an effective power law between 0.5 and 1.0 depending on various parameters. The shape of this curve has been a subject of debate. The TAPPI Tissue Paper Subcommittee of the Physical Properties Committee Interim Report [6] suggests a $t^{0.5}$ relationship, but some TAPPI committee members have argued that a linear relationship is more appropriate. *Figure 1* partially explains this lack of agreement, and highlights the need for a more general curve fitting form when analyzing radial absorbency data. Trying to fit a linear or square-root equation to a complicated logarithmic curve can lead to errors that a simple $n^{th}$ order polynomial can avoid.

## RADIAL FLOW EXPERIMENTS

Radial flow experiments were conducted on a Sherwood ATS radial absorbency tester, and compared with linear absorption data obtained with an x-ray unit. The experimental arrangement for radial absorbency is the same as described in a paper by Beuther and Veith [7] in a study of variability sources in radial absorbency measurements. The ATS equipment provides no information on the structure of the tissue such as pore size distribution, permeability, porosity, density, or other relevant properties. It reports the mass of water absorbed as a function of time. However, by comparing the data of mass flow vs. time to linear flow data, one can use Eq. (9) to infer various properties of the tissue.

There is currently no agreed upon method for how to measure the absorbent rate and much of the disagreement is over whether absorbent rate should be an intrinsic property of the tissue or an in-use parameter. An intrinsic measurement is one with no outside influence on the test results, whereas an in-use measurement would introduce test methodologies that mimic how the tissue behaves in the real world.

An ideal tissue is a compromise between a large pore structure with high porosity to take in a large volume of liquid rapidly and a micro-fine pore structure that can lift liquids to a large height and retain it against opposing forces. The largest source of porosity in a tissue is from the volume between the tissue and a surface to be wiped, or between plies of a multi-ply tissue. Two tissues stacked together will absorb at a rate more than twice that of one tissue due to the addition of an interface. Similarly, a tissue used to wipe up a spill will absorb the spill much faster when held against a surface than if the spill were poured onto the tissue. Since most spills are cleaned up after they hit the table and not before, we contend that an in-use measurement of absorbent rate is a more meaningful parameter than in intrinsic one. Both are valid measurements, but of different properties of the tissue. For this study we will always measure an in-use absorbent rate of tissue by maintaining the tissue in proximity to a flat surface.

The experiments were conducted on 3 inch (76 mm) diameter samples cut from a single sheets of tissue. The tissue is supported on the bottom with a mesh as described in ISO 12625-10 [8]. The monofilament mesh fibers are orthogonally spaced at ½ inch intervals. Differing from ISO 12625-10, we add a top plate to the test as a surface interface. The top plate is a flat plastic cover plate weighing 8 grams and is coated with rain-x® to provide for a repeatable non-wetting surface property as described in [7]. This assures that no unabsorbed water settles on a supporting plate as can occur with a plate beneath the tissue sample. The top plate may also have an added benefit of minimizing error due to evaporation from a wet tissue surface during the test. The bottom support has a central 3 mm diameter orifice through which the water is drawn. The fluid demand reservoir is maintained at a negative head of 3.0 mm.

A typical set of data is shown in *Figure 2*. The y-axis mass has been normalized with basis weight of the tissue sample (gsm, or $g/m^2$). Since the rate varies with time, there is no single parameter in Eq. (9) that completely characterizes the rate. Therefore, absorbent rate needs to be calculated at a particular time. We choose four seconds after test initiation as the time reference, $t_r$, as the initial unstable dynamics during shorter times increase measurement error and longer times can include edge effects if the liquid

front reaches the edge of the sample. The absorbent rate is determined by differentiating the absorption data with respect to time and fitting a linear curve to the differentiated data over a range $t_r \pm 1$ second for smoothing. Data for ten tissues are plotted, five with one side up and five with the other side up. The dashed lines are averages, showing how each side of a tissue can absorb differently.

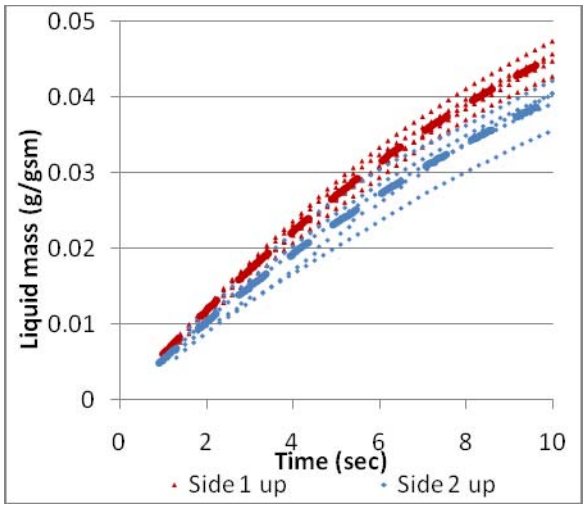


FIGURE 2 Radial Absorbency Data for 1-Ply Towel

## 1-DIMENSIONAL LINEAR EXPERIMENTS

Linear 1-D absorbency data is obtained by taking an x-ray image of an absorbing tissue sheet at different times. Radiographic densitometry or x-ray densitometry is an image analysis technique used to quantify mass of materials. The method provides measures of rate, either as distance vs. time or mass vs. time, but more importantly provides visualization and quantification of the fluid front saturation profile. Saturation represents a measure of both porosity and capacity - the essences of absorbent capacity. Data is presented to show how the partial saturation curve of the fluid front is an indication of the pore network, a key parameter controlling the rate of absorption. When tissue sheets are plied or used as multiple layers additional pore structures are generated having significant impact on absorbent rate. This is true in the interaction of sheets as well as the interface between the sheet and surface the liquid resides on.

Industrial x-ray chambers are customized to conduct analysis of fluid flow in towels and personal care products. Grey scale digital x-ray images are captured, and using image analysis the grey scale is converted to optical density which is then correlated to mass of the liquid. The result quantifies the mass of liquid flowing in plane through the sample. The chamber is capable of rotating the x-ray source to allow visualization in vertical, inclined, or horizontal planes. The data presented here is limited to horizontal flow.

*Figure 3* demonstrates an example of a sequence of images captured during horizontal wicking through a single sheet of premium household tissue. Through image analysis the raw image on the left is segmented into areas 5mm by 5mm and the mass of fluid in each segment determined. To the right are 2-D surface contour plots of fluid mass progressing into the sheet.

The images are digitized and the x-ray data of the linear one-dimensional absorbency flow is related to mass as a function of x, y, and t.

The mass, *M*, of liquid absorbed is obtained as a function of distance and time by summation over y:

$$M(x_i,t) = \sum_j (mass(x_{i,j},t) - mass_{ref}(x_{i,j})) \tag{10}$$

$mass_{ref}$ is the reference mass of the dry substrate and tissue prior to the test initiation.

The data is then normalized with $mass_{ref}$ to give results in terms of $g_{water}$ / $g_{fiber}$. Representative absorbent profile data is shown in *Figure 4*.

The total mass, *M*, of liquid absorbed is obtained as a function of time by summation over all x:

$$M(t) = \sum_i mass(x_i,t) \tag{11}$$

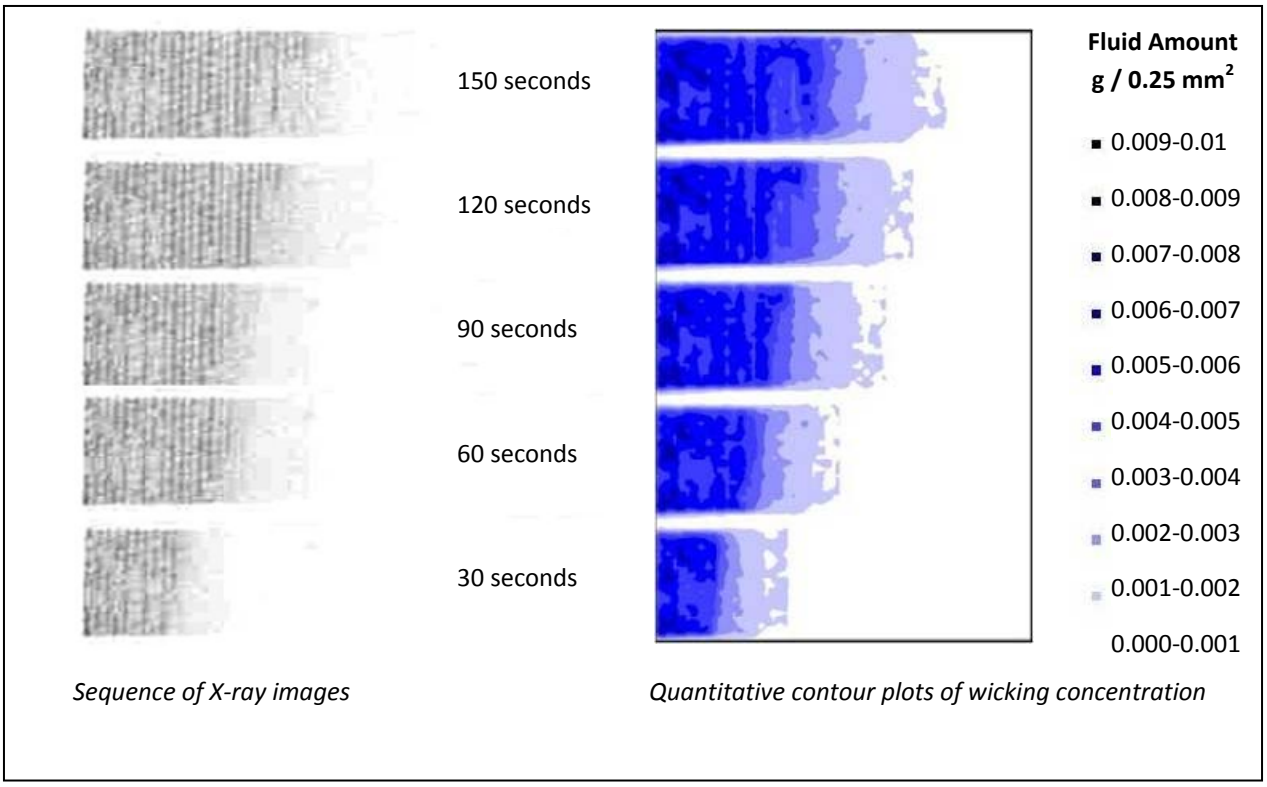


FIGURE 3 Raw x-ray images and converted data

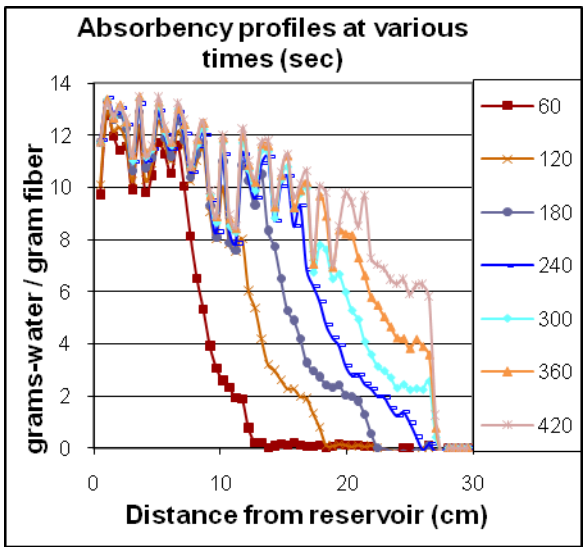


FIGURE 4 Absorbency data profiles, Scott Towel, CD direction, at different times (sec)

A regression curve of the following form is fit to the first five data points:

$$M(t) = A\sqrt{(t - t_0)} \tag{12}$$

where $t_0$ is an offset correction to account for differences in timing between initiation of absorbency and measurement. The slope $A$ is related to the permeability in Eq. (2):

$$A = T \cdot W \cdot \rho \sqrt{\frac{2K\Delta P}{\mu}} \tag{13}$$

*Figure 5* shows the typical shape of this curve. The data sometimes deviates from the initial square-root function at times greater than 200 seconds due to changes in the thickness of the tissue as it swells with liquid, and a fluid front that is not fully saturated. A curve of the form of Eq. (12) is fit to only the initial few points (dashed line) instead of the entire data to achieve a more accurate estimate of the permeability function of Eq. (13).

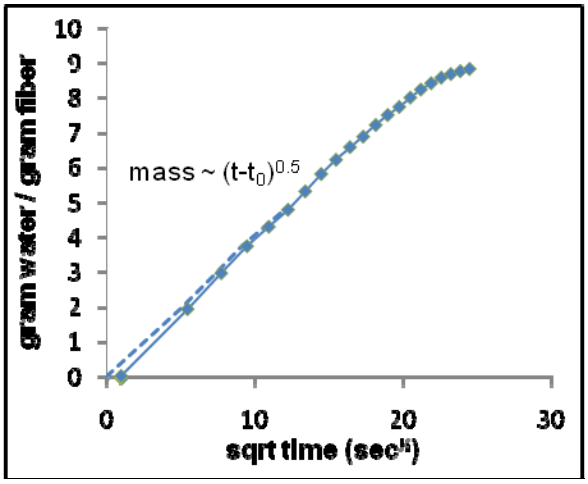


FIGURE 5 Square-root relationship of absorption vs. time

## RESULTS

In order to relate the linear one-dimensional absorbent flow to the behavior of a radial absorbent flow, the unknown thickness is needed. It can be estimated from the absorbent profiles such as *Figure 4* by assuming 100% saturation. This assumption is not valid for the initial liquid front, but it provides a reasonable value for the overall average since most of the tissue is close to 100% saturated. We estimate the thickness as the average over all times at 1 cm from the start of saturation:

$$T = \bar{T}(1\ cm) = \frac{BW}{t_f}\sum_{k=0}^{t_f} m(x_i, t_k),\ i = 2 \qquad (14)$$

$x_i$ = 2 (1 cm) is chosen as a reasonable unbiased thickness estimate. The initial point, $x_i$ = 1, is often lower than average because the grid does not always align perfectly with the edge of the tissue. More distant points are not fully saturated.

The rate of absorbency is also dependent on the direction of flow – machine direction vs. cross machine direction. Radial testing provides an average of both directions, so this directionality of the absorbent flow must be accounted for by measuring the linear absorption in both the MD and CD directions and averaging the results. This is especially important for highly orthotropic structured tissues. In addition, the side in contact with the solid surface also affects the measurements. For both the radial testing and the linear testing, tissues were tested in both orientations.

A series of 20 tests were made using a Scott® brand 1-ply towel, measuring both radial data and linear data. The linear data was converted to an expected radial flow using Eq. (9) after determining the slope "*A*" of Eq. (13). *Figure 6* shows excellent agreement between the data points of the radial flow data and the solid lines from the prediction based on the linear data. Three lines are drawn to show the overlap in variability. The 1-D average line falls directly on top of the radial data. The other two lines are the maximum and minimum 1-D data, and are good bounds to the radial data. The shape of the 1-D curve is slightly flatter than the radial data for time greater than six seconds. This is due to the radial data reaching the edge of the 3 inch sample by this time.

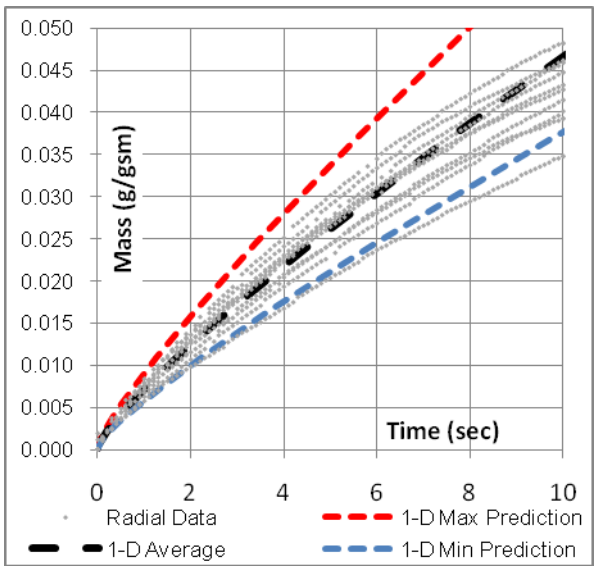


FIGURE 6 Comparison of Radial and Linear Absorbency Data

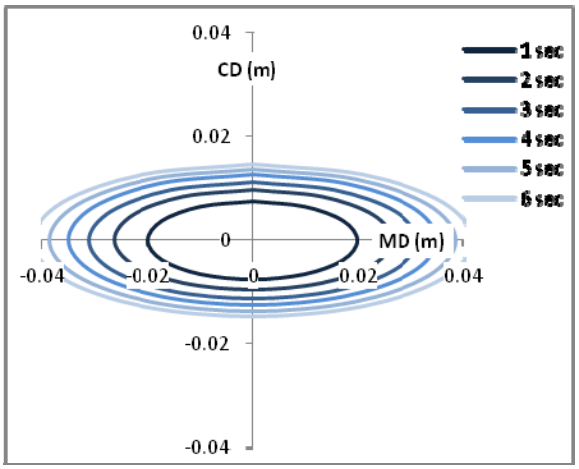


FIGURE 7 Prediction of 2-D Radial Absorption based on Linear Absorption Data – Distance vs. Time

The linear 1-D data can also be transformed to plot radial distance against time, as shown in *Figure 7* to estimate the predicted non-isotropy in the MD and CD directions. It also shows that the fluid front is predicted to reach the edge of a 3 inch diameter tissue sample in the MD direction in about 5 seconds. In order to quantitatively compare the two data sets, the predicted rate at 4 seconds is calculated from both the radial data and the linear theory curve, and again the agreement is excellent, as shown in *Table I.*

TABLE I Towel Data Summary

| | Test Orientation | "*A*" from Eq. (12) | Measured Radial rate at 4 sec g/gsm/s | Predict Radial rate at 4 sec g/gsm/s | Diff, % |
|---|---|---|---|---|---|
| | | | | | |
| Fabric Side Up | MD | 0.986 | | | |
| | CD | 0.297 | | | |
| | Average | 0.642 | 0.00425 | 0.00441 | 3.8% |
| | | | | | |
| Fabric Side Down | MD | 1.045 | | | |
| | CD | 0.326 | | | |
| | Average | 0.686 | 0.00459 | 0.00458 | -0.2% |
| | | | | | |
| | Overall Average | 0.664 | 0.00442 | 0.00449 | 1.6% |

## SUMMARY AND CONCLUSIONS

Absorbent flow solutions for a 1-D linear horizontal flow have been related to radial flow solutions, and x-ray densitometry of 1-D absorption has compared favorably to data from radial absorption. While x-ray densitometry provides a precise and detailed picture of absorbent flow in porous media such as tissue paper, it is somewhat impractical for day-to-day characterization of different products. Conversely, simple radial flow absorbency tests such as are defined in ISO 12625-10 are easy to conduct but have been plagued with difficulties and uncertainties over their significance and accuracy. By relating the 1-dimensional linear absorbency data taken with x-ray densitometry to the average results of a radial absorbency test, a stronger understanding of the radial test data is obtained that reopens opportunities for standardized methods of measuring absorbent properties of tissue paper. The x-ray data confirms the validity of the radial test method, and demonstrates that by defining an experimental procedure, accurate and repeatable data can be measured. Such a procedure might include the following parameters along with their benefits:

1. Testing of single sheet of tissue - avoid multiple and variable number of interfaces.
2. Testing a larger 3 inch (76 mm) diameter sample - avoid edge effects.
3. Supporting the sample on a monofilament mesh - avoid unabsorbed water.
4. Covering the sample with non-wetting cover plate - correctly simulate in-use performance.
5. Testing both sides of the tissue – avoid variability from sidedness.

These test parameters ensure that an absorbent rate measurement provides an accurate representation of in-use properties of the tissue.

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