

Influence of Processing Conditions On Melt Blown Web Structure: Part 1 – DCD

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Abstract

We begin an effort to quantitatively measure the influence of processing conditions on the detailed structure of commercial polypropylene melt blown (MB) webs. In this paper, we report the influence of die-to-collector distance (DCD) on fiber entanglement, fiber orientation and pore structure in webs. This enabled us to quantify the influence of DCD on web structure as well as achieve greater understanding of the commercial MB process.

Introduction

The melt blowing (MB) process is a commercially important, single-step process that converts polymer raw material directly into web. An illustration of the basic MB process is provided in *Figure 1*. Polymer is melted in an extruder, pumped through die holes and then the melt enters high-speed, hot air streams. Web structure (i.e. a fiber network) begins to develop when fiber entanglement first occurs (within 1 cm of the die) but network structure is dynamic and becomes fixed only when fibers contact the collector and their motion ceases. *Figure 1* indicates that numerous polymer, air and equipment variables would be expected to influence web structure development. Many variables such as fiber entanglement are known to influence nearly every aspect of fiber and web structure development during MB. As a result, changes in nearly any processing variable influence web

structure (and properties) in complex ways. This explains in large part why the MB process has been difficult to understand even though it has been commercially successful for fifty years.

Much research has been conducted to relate commercial MB processing conditions to web properties and, to a lesser extent, web structure [1-5]. However, few studies have quantified these relationships and fewer have reported web structure in significant detail.

We have begun an effort to quantitatively determine the influence of major processing conditions on the detailed structure of polypropylene webs produced with a commercial MB process. In this paper, we address the influence of DCD on fiber entanglement, fiber orientation and pore structure in webs. In subsequent reports, we will evaluate additional processing variables such as primary airflow rate and water quenching as well as additional web structural features such as basis weight uniformity and single fiber diameter. We hope this work will enable us to achieve more detailed and quantitative knowledge of the influence of processing conditions on web structure as well as achieve greater understanding of the commercial MB process.

Experimental Procedures

We prepared thirty 21 g/m² webs using ExxonMobil PP3505GE1 polypropylene of 400 melt flow rate. The MB line used to prepare webs was a 115 cm (45 inch) wide horizontal commercial MB line with a 200 cm (79 inch) diameter rotating drum collector. The die had 14 holes/cm (35 holes/inch) with

hole diameters of 305 μm (0.0120 inch). We used primary airflow rates ranging from 370 to 700 ft^3/min and die-to-collector-distances from 22 to 40 cm (8.5-15.0 inch).

Fiber bundle analysis [6], fiber orientation analysis [6] and pore analysis [7] were measured quantitatively off-line using WebPro, an automated image analysis-based instrument [8]. A substantial effort was made to sample web structure adequately. This involved measuring approximately 400 locations for pore analysis, 600 locations for fiber entanglement analysis and 600 locations for fiber orientation analysis in each web.

Results and Discussion

The discussion below addresses the influence of DCD on the structure of fully-formed webs. We will discuss how DCD influences fiber entanglement, fiber orientation and pore structure in webs.

Fiber Entanglement

When fiber entanglement occurs during MB, the number and size of fiber bundles increase in fully-formed webs. We assessed fiber entanglement by analyzing the size of fiber bundles at 600 locations across the full width of each web. Figure 2 shows fiber bundle size distributions for various DCD's and a slow primary airflow rate (370 ft^3/min), a medium airflow rate (500 ft^3/min) and a fast airflow rate (630 ft^3/min).

This figure shows that fiber entanglement was dependent on DCD at all primary airflow rates. When DCD was increased, the percentage of fine fiber bundles decreased and the percentage of coarse fiber bundles increased. We also see that the influence of DCD on fiber entanglement was greater for smaller bundle sizes than larger bundle sizes. For example, increasing DCD from 22 cm to 40 cm for the 630 ft^3/min air-flow condition reduced the percentage of bundles in the 5-9 μm size substantially (from 35% to 15%) whereas the percentage of bundles in the 30-34 μm bundle size increased only moderately (from 2% to 7%).

The data in Figure 2 also show that the influence of DCD on fiber entanglement became reduced for increasingly larger DCD's (i.e. it is more difficult to distinguish bundle data for webs collected at larger DCD's than at smaller DCD's). For example, bundle data in medium and large bundle size regions for the 630 ft^3/min airflow condition can be easily distinguished for webs collected at 22, 24 and 26 cm DCD but not for webs collected at 28 – 40 cm DCD.

Next, we extracted quantitative parameters from bundle size distributions. Mean bundle diameter was computed for each distribution and then averaged for the six primary airflow rates at each DCD to reduce data noise. We searched for

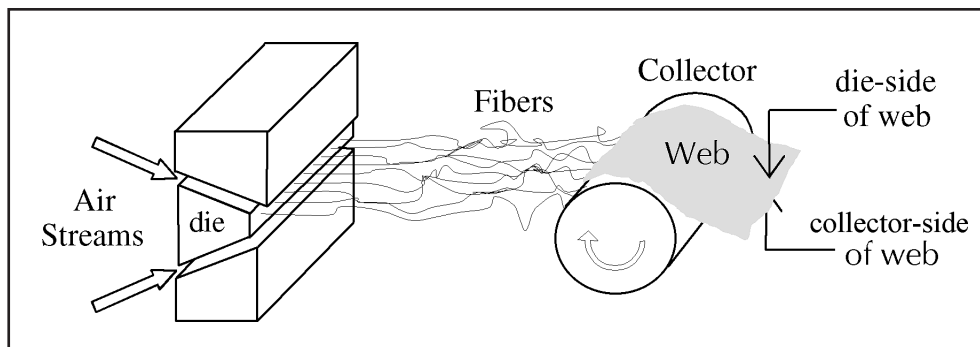


Figure 1
ILLUSTRATION OF THE MELT BLOWING PROCESS

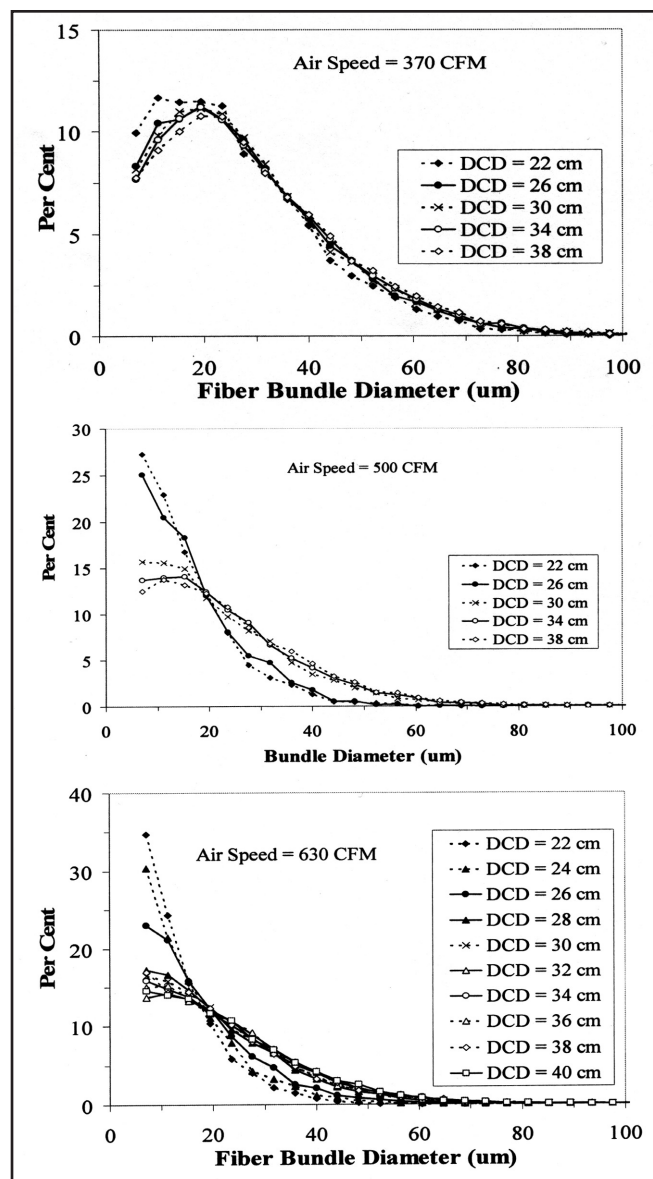


Figure 2
FIBER BUNDLE SIZE DISTRIBUTIONS AT
VARIOUS DIE-TO-COLLECTOR-DISTANCES
FOR 370 FT^3/MIN , 500 FT^3/MIN AND 630
 FT^3/MIN PRIMARY AIRFLOW.

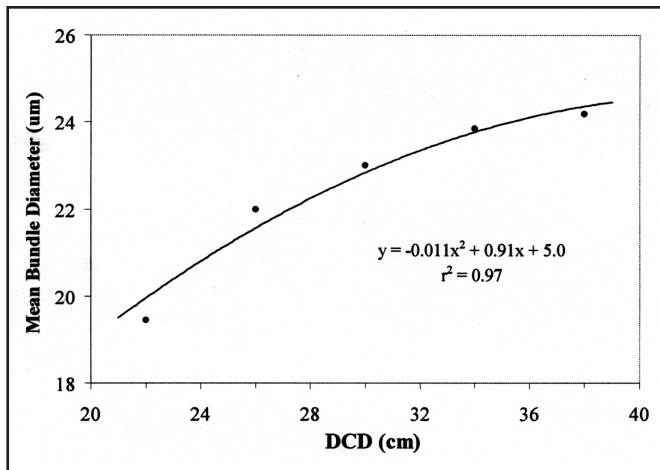


Figure 3

MEAN FIBER BUNDLE SIZE AVERAGED FOR SIX PRIMARY AIRFLOW RATES AT EACH DCD

equations that fit the data after fixing the y-intercept at 5.0 um. This fixed the mean bundle diameter equal to the approximate size of individual fibers near the die where little entanglement normally occurs. *Figure 3* provides our results and shows that mean bundle size increased when DCD was increased. This figure also shows that the relationship between mean bundle size and DCD was not linear. A second order polynomial provided the best fit to the data ($r^2 = 0.97$) for the DCD range we studied. Nonlinearity is in agreement with the trend previously observed qualitatively in *Figure 2*.

Figure 3 shows that the influence of DCD on fiber entanglement became reduced at increasingly larger DCD's. This can be explained by considering the affect of previous fiber entanglement on the probability of additional fiber contact and entanglement. Near the die, fibers are spaced close together (approximately 0.7 mm intervals in a plane of shallow depth) so the probability of a fiber contacting and entangling with other fibers is large. After an individual fiber becomes entangled with other fibers, the population of fibers near the entangled fibers is reduced since some of the fibers previously located nearby have already been incorporated within the fiber bundle. This leads us to expect that fiber entanglement reduces the probability that additional fiber contact/entanglement will occur. The data in *Figure 3* suggest that this explanation is applicable through the whole DCD range we studied. *Figure 3* also suggests that the probability of additional fiber entanglement may become quite small at very large DCD's.

Next, we evaluated the maximum fiber bundle size for each bundle distribution by averaging the maximum bundle sizes at each DCD for the six primary airflow rates and fitting curves after fixing the y-intercept at 5.0 um. The result of this procedure is provided in *Figure 4*. This figure shows that the relationship between maximum bundle size and DCD also was markedly nonlinear. Similar to *Figure 3*, the best fit to the data in *Figure 4* was provided by a second order polynomial ($r^2 = 0.94$).

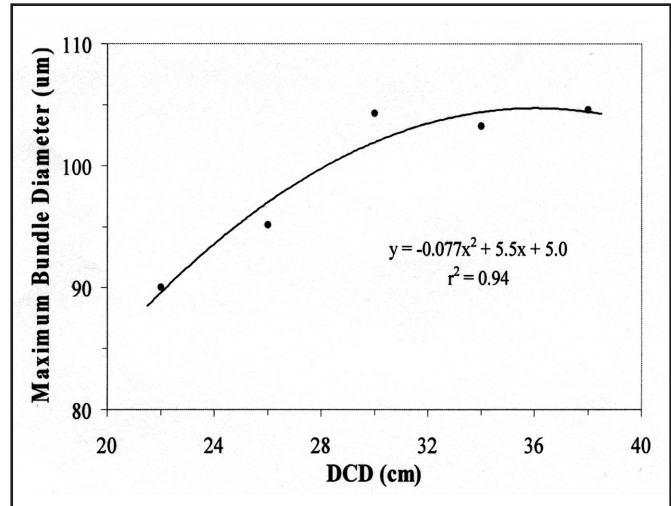


Figure 4

MAXIMUM FIBER BUNDLE SIZE AVERAGED FOR THE SIX AIRFLOW RATES AT EACH DCD.

The influence of DCD on maximum bundle size was similar to that obtained for mean bundle size. That is, the influence of DCD on fiber entanglement became reduced at increasingly larger DCD's. However, comparison of *Figures 3 and 4* suggest that DCD affects were reduced sooner for maximum bundle size than for mean bundle size. This observation is consistent with the previously discussed concept that considered the influence of previous fiber entanglement on the probability of additional fiber contact and entanglement. That is, it is reasonable to expect that the population of fibers near the largest fiber bundle generally has been reduced more than populations near smaller sized bundles. This leads us to expect that the largest bundle has the smallest probability of engaging in additional fiber contact and entanglement.

Overall, our evaluation of fiber entanglement leads us to expect that increasing DCD increases entanglement most significantly for single fibers and small fiber bundles. We should not necessarily expect the largest fiber bundles to grow increasingly larger as DCD is increased. We should also expect that even small DCD changes within the normal DCD range used for commercial processing will significantly affect web basis weight uniformity since entanglement concentrates fiber mass within fiber bundles rather than distributing fibers more randomly over a larger web area. Improvement in web basis weight uniformity commonly observed as DCD is reduced most likely results in large part from a decrease in fiber entanglement. On the other hand, our data imply that extremely large DCD's (e.g. 3-4 m) would not necessarily produce fiber bundles as large as we might expect on the basis of bundle formation at conventional DCD's.

Similar arguments can be made to predict the influence of DCD on other web properties. For example, we should expect that small DCD changes may affect web cover significantly since increasing DCD reduces the population of single fibers and small fiber bundles most significantly which could effectively reduce fiber cover in some cases.

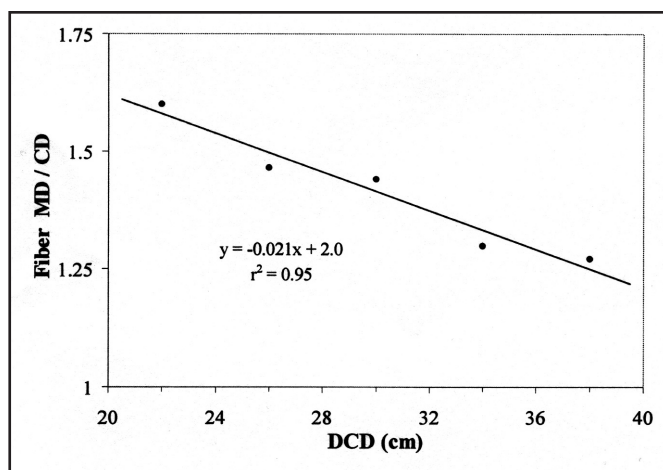


Figure 5
FIBER ORIENTATION AVERAGED FOR THE
SIX AIRFLOWS AT EACH DCD.

Fiber Orientation

Melt blown webs typically exhibit very broad fiber diameter distributions. Consequently, it is generally more meaningful to measure fiber orientation in terms of the amount of fiber cross-sectional area aligned in each direction rather than the number of fibers aligned in each direction. We measured the orientation direction and cross-sectional area of numerous fibers simultaneously at 600 locations across the full width of each web. Once measurements were obtained for many thousands of individual fibers for each web, we computed the MD/CD ratio which represents the amount of fiber cross-sectional area oriented near the machine direction (MD ± 20 deg) divided by the amount of fiber cross-sectional area oriented near the cross direction (CD ± 20 deg). This ratio equals one for isotropic fiber orientation, exceeds one for preferred MD orientation and is less than one for preferred CD orientation. To reduce data noise, we averaged MD/CD values for webs produced with the six primary airflow rates at each DCD. Results are provided in *Figure 5*.

As is usual for MB webs, all of our webs exhibited preferential MD fiber orientation since MD/CD exceeded one in all cases. *Figure 5* shows that increasing DCD reduced MD orientation linearly ($r^2 = 0.95$) through the DCD range we evaluated.

We can explain this observation on the basis of drag forces near the collector during fiber laydown. Drag forces are large at two basic locations of the conventional MB process [9]. Near the die, air speed is very fast and fiber speed is very slow so aerodynamic drag is large. Near the collector, air speed is still quite fast and fiber speed decreases to zero during laydown so aerodynamic drag increases significantly during laydown.

Since fiber speed is reduced to zero for all processing conditions, the magnitude of the drag force experienced by fibers during laydown is determined primarily by the speed of air in

the laydown region of the collector. Since the collector is located further from the air source at larger DCD's, we should expect the speed of air arriving at the collector and the drag force acting on fibers during laydown to decrease when DCD is increased [9]. Since the direction of airflow in the laydown region of a rotating drum collector is the MD, increasing DCD ought to result in reduced MD orientation in webs. *Figure 5* provides a quantitative assessment of this effect and shows that the MD/CD ratio decreases linearly with increasing DCD.

Pore Structure

The size, shape and orientation of numerous individual pores were measured for at least 400 locations across the full width of each web using WebPro [7]. Pore measurements obtained in this manner are physically meaningful only for relatively thin webs where pores are approximately two-dimensional. Webs produced for this study were relatively thin (basis weights were 21 g/m²) so pore measurements were easy to interpret physically.

Once pore measurements were obtained for many thousands of individual pores for each web, pore cover was computed. Pore cover represents the percentage of web area covered with pores (pore cover plus fiber cover = 100%). Next, we searched for curves that fitted the data best.

Figure 6 shows pore cover data for various DCD's and primary airflow rates. This figure shows that pore cover varied by more than a factor of ten among the primary airflows we studied at any DCD. For example, pore cover ranged from 7.5% (370 ft³/min primary airflow) to 0.7% (700 ft³/min airflow) when DCD was 22 cm. This variation probably resulted from differences in single fiber diameter since one would expect higher primary airflow to generally produce finer fiber diameters which, in turn, increase fiber cover and reduce pore cover.

Figure 6 shows that pore cover was influenced by DCD linearly but the magnitude of the affect varied substantially with primary airflow rate. Pore cover varied markedly with DCD at low (slope = 0.48) but not high (slope = 0.00) airflow rates. This is explained best in the following way. When DCD was increased at low airflow rates, fiber entanglement increased so fiber cover was effectively reduced and pore area increased. On the other hand, fiber cover at high airflow rates was so large that reduced fiber cover from greater fiber entanglement was negligible. That is, fiber entanglement probably reduced fiber cover at larger DCD's but fiber cover was great enough at large airflows that increased entanglement was not likely to form pores that extended through the whole web thickness. It is likely that pore cover would have increased at high airflow rates when DCD was increased if we had collected webs of lower basis weight since fiber cover would have been reduced. Similarly, we probably would not observe a dependence of pore cover on DCD at any airflow rate if we had collected webs of substantially greater basis weight.

Interpretation of pore cover data can be facilitated by exam-

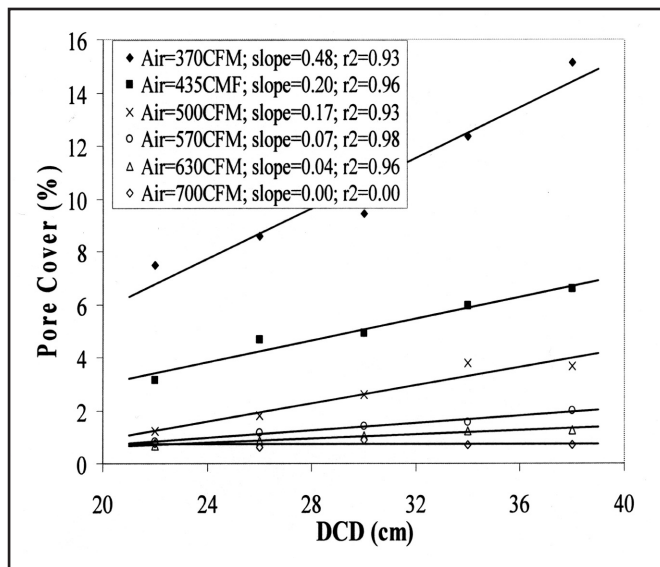


Figure 6
PORE COVER FOR VARIOUS DCD'S AND
PRIMARY AIRFLOW RATES

ining the two basic structural features that contribute most to pore cover – pore size and the number of pores. Pore size information is provided in *Figure 7* in terms of the mean diameter (equivalent circle diameter) of pores in each web.

Comparison of *Figures 6 and 7* shows that general trends for pore cover and pore size were similar. That is, both pore cover and pore size generally decreased when primary airflow rate increased for any particular DCD. In addition, both pore cover and pore size were affected by DCD linearly and the magnitude of the affect varied with primary airflow rate. These similarities indicate that the affects of DCD and primary airflow on pore cover probably were related to their influence on pore size. This is reasonable since increasing DCD and decreasing primary airflow would be expected to reduce fiber cover and consequently increase both the amount of pore cover and the size of pores.

Figure 8 provides the number of pores per unit web area for each web. This figure shows that the number of pores detectable by optical microscopy in webs was markedly influenced by primary airflow. This is reasonable since finer fiber diameters generally are produced when primary airflow rate is increased and that increases fiber cover and reduces the number of pores detectable in webs by optical microscopy. *Figures 6 and 8* show that pore cover and the number of pores both decreased when primary airflow rate was increased for any particular DCD.

In contrast to this, the influence of DCD on the number of pores was similar for all primary airflow rates even though the influence of DCD on pore cover decreased systematically when primary airflow was increased. To reduce data noise, the number of pores in each web was averaged for the six airflow rates at each DCD and is also provided in *Figure 8*. This shows that the number of pores depended only slightly on DCD. This is reasonable since one would expect the number

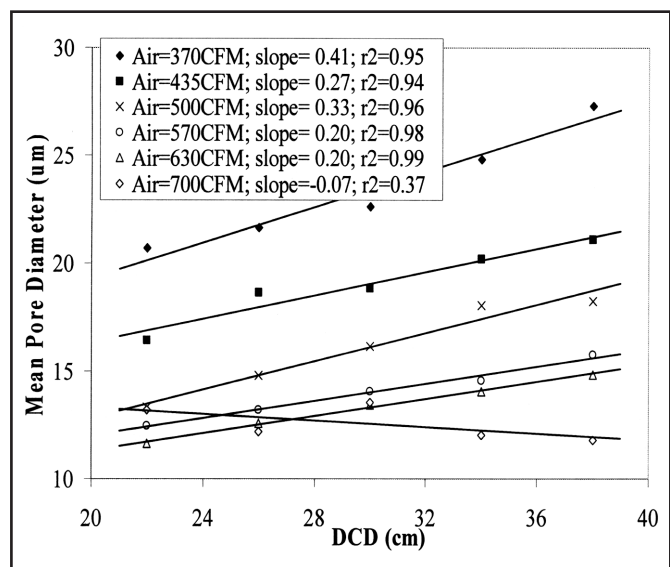


Figure 7
MEAN PORE DIAMETER FOR VARIOUS
DCD'S AND PRIMARY AIRFLOW RATES

of pores to depend primarily on the amount of fiber length present in a unit web area and fiber diameter has been shown to change only slightly with increasing DCD at distances well beyond the die [10].

Overall, our data indicate that increasing DCD increased pore cover primarily because the size rather than the number of pores increased. In turn, increasing DCD increased pore size because fiber entanglement increased at larger DCD's and entanglement reduced the effective fiber cover in webs. On the other hand, increasing primary airflow rate reduced pore cover because both the size and number of detectable pores decreased. This apparently occurred because finer fibers were formed at greater airflow rates and finer fibers increased fiber cover.

Next, we examined the influence of DCD on the shape of pores. *Figure 9* provides the mean pore aspect ratio averaged for the six primary airflow rates at each DCD. This figure shows that pore aspect ratio increased quite linearly when DCD increased ($r^2 = 0.99$). Since circularly-shaped objects exhibit aspect ratios of one, *Figure 9* shows that, on average, pores in our MB webs were substantially elongated. Since we previously showed that these webs exhibited preferred MD fiber orientation rather than isotropic fiber orientation, it may not be surprising to observe pores that were elongated rather than isotropic in shape.

However, we previously showed that increased DCD reduced preferred MD fiber orientation in webs. This would lead us to expect that increasing DCD would cause pore shape to become more isotropic (overall, less elongated) if we consider only global fiber orientation. *Figure 9* clearly shows that pore shape became more elongated when DCD was increased. This can be explained on the basis of local (rather than global) fiber orientation. Fiber entanglement produces fibers that are

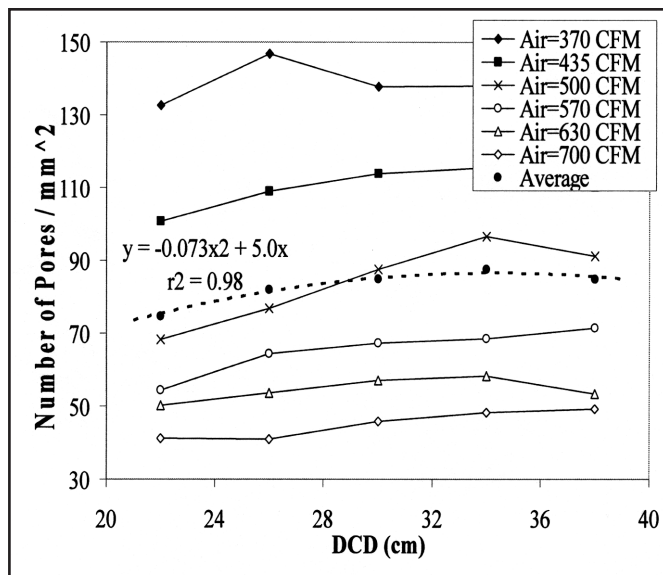


Figure 8
NUMBER OF PORES PER MM² WEB AREA
FOR VARIOUS DCD'S AND PRIMARY
AIRFLOW RATES

arranged predominantly in a collinear manner in individual bundles. Consequently, individual fiber bundles in MB webs possess marked local fiber orientation regardless of whether or not fibers in a web exhibit preferred fiber orientation on a global scale. Increased fiber entanglement associated with increased DCD can be expected to result in more collinearly oriented fibers on a local level and thus a greater number of long, narrow pores in webs.

To assess pore orientation in webs, we measured the orientation angle of the major axis of each pore. During this process, the MD was defined as the 0 deg direction and the CD was defined as the ± 90 deg directions. The mean pore orientation angle was computed for each web based on absolute values of individual pore orientation angles. When this was done, isotropic pore orientation is expected to exhibit a mean angle of 45 deg, preferential MD pore orientation will exhibit a mean angle < 45 deg and preferential CD pore orientation will exhibit a mean angle > 45 deg. To reduce measurement noise, mean orientation angles were averaged for the six webs produced with different airflow rates at each DCD. Results are provided in *Figure 10*.

This figure shows that pores in our webs exhibited preferential MD orientation since mean orientation angles were less than 45 degrees. This is consistent with our previous observation (Fig. 5) that fibers in our webs exhibited preferential MD orientation on a global scale. *Figure 10* shows that increasing DCD resulted in disorientation of pores since mean pore orientation angles increased toward 45 degrees when DCD was increased. This trend also is consistent with *Figure 5* which showed that global MD fiber orientation was reduced when DCD was increased.

Overall, we observed that pore orientation correlated with global fiber orientation whereas pore shape correlated with

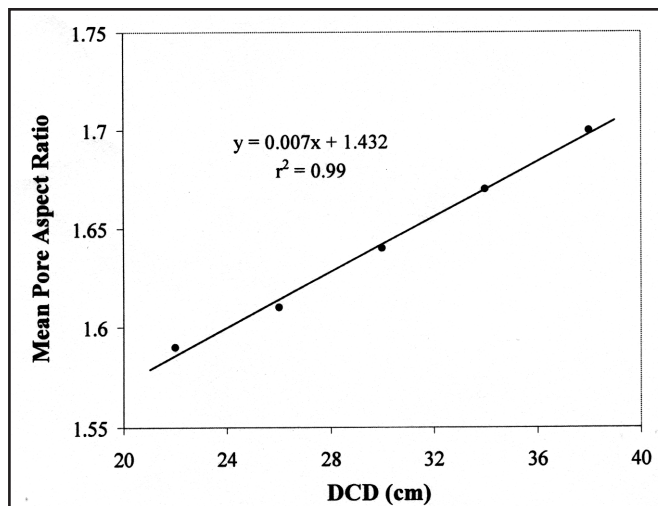


Figure 9
MEAN PORE SHAPE AVERAGED FOR THE SIX
AIRFLOWS AT EACH DCD

local rather than global fiber orientation. Both pore orientation and pore shape were markedly influenced by DCD.

Conclusions

We reported quantitative experimental measurements of the influence of DCD on fiber entanglement, fiber orientation and pore structure in webs. We observed the following effects:

Increasing DCD increased fiber entanglement. Fine bundles were formed more readily than coarse bundles when DCD was increased and the influence of DCD on fiber entanglement was reduced at larger DCD's. These effects were thought to occur because larger bundles were surrounded by fewer nearby fibers during MB and thus were less likely to contact additional fibers to entangle further.

Increasing DCD noticeably reduced global preferential MD orientation of fibers in webs. This was explained on the basis of aerodynamic drag since the speed of air arriving at the collector is reduced when DCD increases so the drag force available to orient fibers in the direction of airflow (MD) is reduced when laydown occurs at a larger DCD.

Increasing DCD increased pore cover because the size rather than the number of pores increased as a result of additional fiber entanglement. At higher primary airflow rates where fiber cover approached 100%, DCD influenced pore cover less noticeably because entanglement did not overcome the greater fiber cover that resulted from higher airflow rates. Increasing DCD increased the aspect ratio of pores because local fiber orientation increased as a result of fiber entanglement. Increasing DCD reduced preferential MD orientation of pores because global fiber orientation decreased.

We should expect even small DCD changes to affect web basis weight uniformity, web cover and numerous other web properties since entanglement is influenced by DCD and entanglement causes fiber mass to become concentrated in fiber bundles rather than being distributed over a larger web area.

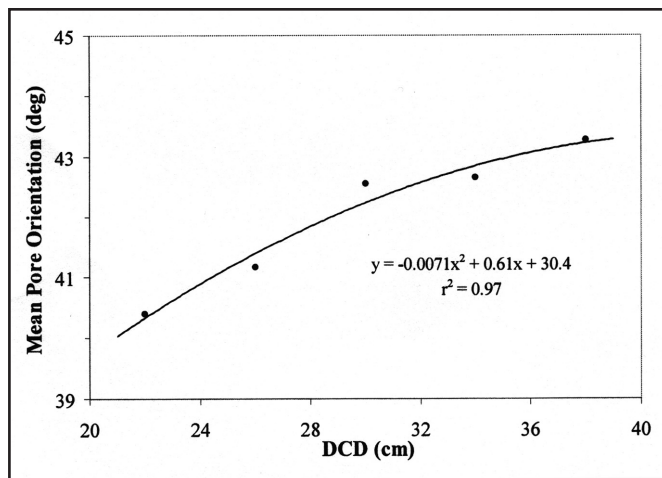


Figure 10
MEAN PORE ORIENTATION ANGLE
AVERAGED FOR THE SIX AIRFLOWS AT
EACH DCD

the Melt Blowing Process," *International Nonwovens Journal*, 8(1), 60-65 (1999) — INJ

References

1. Malkan, S. R. and L. C. Wadsworth, "Process-Structure-Property Relationships in Melt Blowing of Different Molecular Weight Polypropylene Resins, Part I: Physical Properties," *Journal of Nonwovens Research*, 3(2) 21-34 (1991)
2. Lee, Y. and L. C. Wadsworth, "Effects of Melt-Blowing Process Conditions on Morphological and Mechanical Properties of Polypropylene Webs," *Polymer* 33, 1200-1209 (1992)
3. Lee, Y. and L. C. Wadsworth, "Effects of Melt-Blowing Process Conditions on Morphological and Mechanical Properties of Polypropylene Webs," *Polymer* 33, 1200-1209 (1992)
4. Sun, Q., D. Zhang, B. Chen and L. C. Wadsworth, "Application of Neural Networks to Meltblown Process Control," *Journal of Applied Polymer Science*, 62, 1605-1611 (1996)
5. Farer, R. et al., "Study of Meltblown Structures Formed by Robotic and Meltblowing Integrated System: Impact of Process Parameters on Fiber Orientation," *International Nonwovens Journal*, 11(4), 14-21 (2002)
6. Huang, X.C. and Bresee, R.R. "Characterizing Nonwoven Web Structure Using Image Analysis Techniques. Part II: Fiber Orientation Analysis in Thin Webs," *Journal of Nonwovens Research*, 5(2), 14-21 (1993)
7. Huang, X.C. and Bresee, R.R. "Characterizing Nonwoven Web Structure Using Image Analysis Techniques. Part I: Pore Analysis in Thin Webs," *Journal of Nonwovens Research*, 5(1), 13-21 (1993)
8. Yan, Z. and Bresee, R.R. "Flexible Multifunction Instrument for Automated Nonwoven Web Structure Analysis," *Textile Research Journal*, 69, 795-804 (1999)
9. Bresee, R.R. and Qureshi, U.A. "Fiber Motion Near the Collector During Melt Blowing. Part I: General Considerations," *International Nonwovens Journal*, 11(2), 27-34 (2002)
10. Yin, H., Yan, Z. and Bresee, R.R. "Experimental Study of