JOURNAL OF
Applied Polymer
SCIENCE

Fabrication of micro-meltblown filtration media using parallel plate die design

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ABSTRACT: Meltblown fibers are typically produced using a die technology based on the slot concept, an extension of the sheet die technology with a series of holes substituting the center rectangular slot of the sheet die. While this prevalent technology has met with considerable success, an economical, facile design would be desirable. In this study a new parallel plate die concept to fabricate micro-meltblown fibers that offers simplicity, ease of use, and low cost was examined. The new die concept had parallel plates forming channels for polymer melt to flow through with a set of air holes surrounding them. This die design produced meltblown fibrous media with fibers in the range of 3–10 μm with pore size between 20 and 60 microns. The underlying mechanisms leading to such large fiber size formation and its implication in air filtration performance has been discussed. While conventional meltblown die generates fibers of smaller diameter and webs with higher filtration efficiency than the parallel plate geometry, design modifications could enhance the parallel plate meltblown die performance and make it a viable alternative. These die adaptations that include reducing air flow resistance, increasing the number of air nozzles around the polymer nozzles, recessing the polymer spinnerets above the die face, and having inclined air channels to increase the drag force on the fibers has been discussed. © 2015 Wiley Periodicals, Inc. J. Appl. Polym. Sci. **2016**, *133*, 42998.

KEYWORDS: fibers; fiilter media; filtration; meltblowing die; meltblown; microfibers; nonwovens

Received 6 July 2015; accepted 30 September 2015
DOI: 10.1002/app.42998

INTRODUCTION

Meltblowing (MB) is a nonwovens technology that produces engineered fabrics of randomly laid man-made fibers in a single step. Typically, molten polymer resins are fed to a MB die head (Figure 1) whereupon high speed hot air jets impinge upon the polymer streams once they exit the die spinnerets and reduce their diameter by the effect of the drag force.[1–3] Because of the high surface area and tight pore size of these microfiber meltblown fabrics, they are highly utilized in fabricating fibrous filtration media.[1] The most common MB die technology currently used was developed in the mid-1950s, and is an extension of "slot" concept originally used for making film sheets. In this approach, the rectangular slot die used to make flat films is replaced by a series of nozzles or holes.[4] The second MB technology that is currently utilized commercially is the biaxial Schwarz MB die that was developed in the 80s, and is in the form of arrays of annular jets.[5] Typical Schwarz MB die has either square or triangular air holes surrounding the polymer capillaries and is designed to have multiple rows to allow for up to 12,000 nozzles per meter.[6] Another MB die technology patented by Kwok (1996)[7,8] is in the form of parallel plates assembly (Figure 2) that consist of holes for polymer melt to flow through them and another set of holes surrounding the polymer holes for air to flow through them. The parallel plate MB die technology is simple in design, low in cost compared with its counterparts (typically one-tenth the cost of a conventional MB die) and easy to use. These attributes have rendered this useful in adhesive applications, that do not require high web uniformity, and in which the MB layer is used to bond two different substrates. Other industries have also taken advantage of the parallel plate technology for making baby diaper elastics, feminine napkin core stabilization and adhesive strip, industrial filter material lamination, and filter mask lamination.[9] Expanding the scope of this technology to other applications including filtration would be highly desirable given its low lost, and the ever expanding markets in these areas. However, few studies, if any, have been conducted to assess the performance and fundamentals of the parallel MB approach.

Several studies have however been conducted on the slot MB die and its performance, including examining methods to reduce the fabricated fiber diameter, improving, and controlling the web filtration properties, and investigating the effect of die

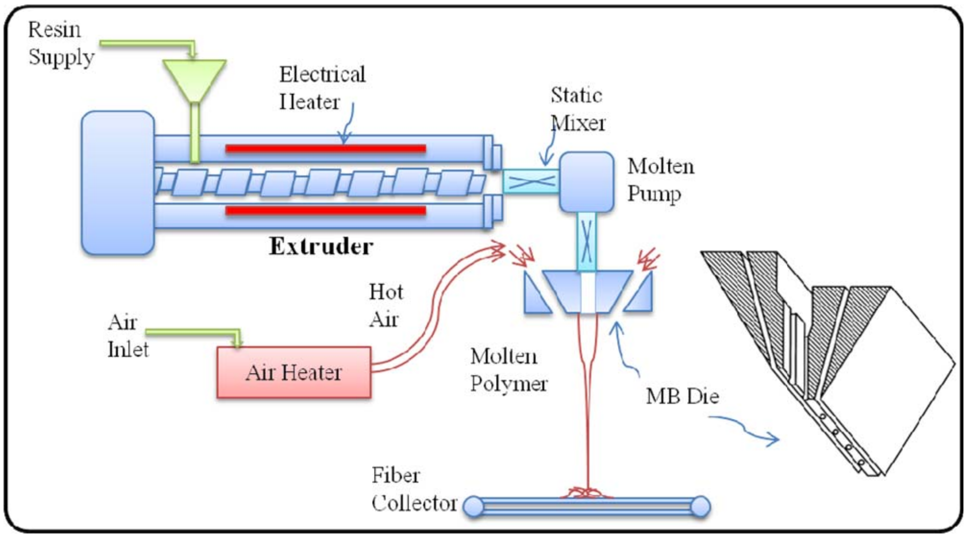

Figure 1. Schematic drawing of a typical MB process with a conventional slot (CS) die, (not drawn to scale). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

geometry on process aerodynamics and fiber properties.[10–22] Several one-, two-, and three-dimensional models have also been developed for the slot MB die.[17–22] The effect of the air channel angle and the polymer spinneret position on the air flow field under the slot MB die face was also investigated both experimentally[10] and theoretically using computational fluid dynamics (CFD) simulations.[13–15] Krutka *et al.*[13] showed experimentally that using a blunt slot MB die produces a lower maximum centerline velocity and that the centerline velocity profile decays at a higher rate than that observed using a sharp MB die. Kurtka *et al.*[14] also used CFD to simulate different MB die configurations, and found that increasing the nosepiece recession leads to an increase in the maximum centerline velocity and the air velocity at the highest recession was three times the air velocity for a slot MB die with polymer nozzles at the same level as the die face. Higher maximum centerline air velocity in the z-direction, is favorable as it leads to an increased rate of fiber attenuation (i.e., finer fiber) for a given air throughput. Krutka *et al.*[16] analyzed the multiple jets in the biaxial MB die and investigated the effect of the interaction of the multiple rows and columns on the air flow field below the die face. They found that the spreading rate for the center jets of the multi hole dies were similar to each other and close to 0.5, but the spreading rate for a single annular jet is close to one.[16]

While considerable research work has focused on the slot MB die, very limited research exists on the performance of the parallel plate MB die technology. An understanding of the potential of the parallel plate die in producing meltblown fibers is therefore desirable. In this study, we examined the capabilities of the parallel plate MB die technology to fabricate microfibrous meltblowns and compared its performance to the conventional meltblowns produced using a slot die technology. Specifically, we examined fiber size, web formation, air permeability, and filtration efficiency which are key characteristics for filtration application. We pointed out to the key attributes of this die design and explained its potential for producing fine meltblown fibers using a low cost and simple die design. Our initial investigation showed that the parallel plate die design produces high internal

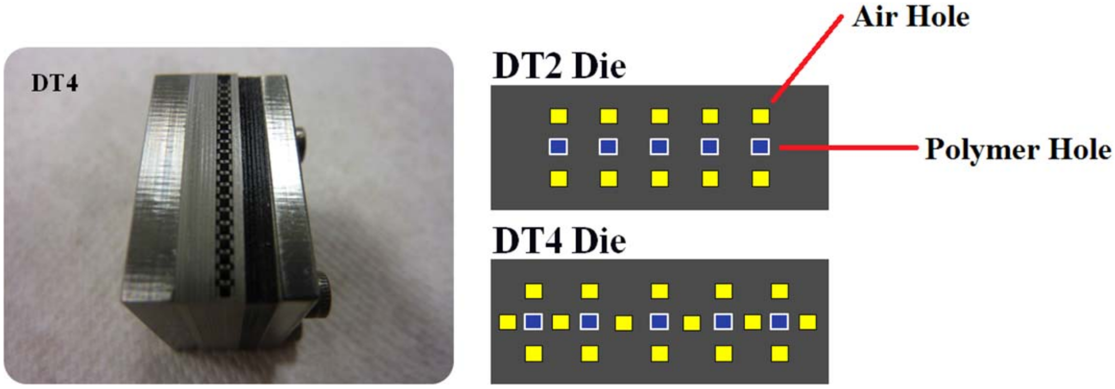

Figure 2. Parallel plates die design of different configurations. DT2 is a Dynatec die where every polymer hole is surrounded by two air holes while DT4 is a Dynatec die where every polymer nozzle is surrounded by four air holes. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

resistance to air flow. Modification of the die to increase air flow displayed improved results but not enough to outperform the standard MB die. Based on our findings, we recommend further adaptation of these photochemically etched parallel plates in order to reduce the internal resistance to air flow and achieve better or comparable performance to the conventional MB die.

EXPERIMENTAL

MB Unit

A small scale MB line at the Nonowovens Institute (NWI) located at North Carolina State University was utilized to conduct this study. The base component of the system is a 1.9 cm (3/4 inch) single screw extruder with an extended 30:1 barrel. The extruder barrel is surrounded with four band heaters to establish four individual temperature zones. During operation, polymer pellets are melted and pressurized using the extruder that is mounted horizontally. The final temperature zone, Z4, was set to the desired temperature 255°C, while the temperatures in the other zones, Z1, Z2, and Z3 were set to 150°C, 175°C, and 210°C, respectively. The 255°C is a common operating melt temperature for PP with others using similar melt temperature for the same polymer.[2] In addition, degradation of this polymer has been found to begin at a higher temperature with only 1% degrading at 315°C.[23] Another study by Mengeloglu *et al.*[24] reports an even higher onset degradation temperature for PP, 375°C, with a peak degradation temperature of 420°C. Immediately after the extruder, we have a static mixer followed by a 5 cc gear pump to precisely feed the MB die with the desired polymer throughput. Compressed air for blowing the polymer melt was heated using a 20 kW electric heater, and then fed by two hoses to each side of the 15 cm MB die.

Die Designs

We used two types of parallel plate MB dies that were donated by *ITW Dynatec*. The first model, the 106356F (referred to as DT2), has square polymer nozzles of an equivalent diameter of 180 μm with nozzle density of 7 nozzle/cm (17 nozzle/in), (Figure 2). Parallel to each polymer nozzle, we have two other nozzles, one from each side, for air to flow in a parallel direction to the polymer streams to attenuate them. The polymer nozzles protruded from the die face by 1 mm. The second Dynatec MB die design, the 116632 (referred to DT4 from now on), has approximately 7.5 nozzle/cm (19 nozzles/inch), with an equivalent diameter of 180 µm, (Figure 2). Parallel to each polymer nozzle, we have four other nozzles for the hot air required for fiber attenuation. The polymer and air nozzles were flush mounted with the die face. The Dynatec dies were manufactured in the form of 2.5 cm long MB dies. Our spin pack was 15 cm long that could be assembled from six little dies of either model (Figure 3).

The performance of the new Dynatec die technology was compared with a 15 cm long conventional slot MB die (from now referred to as the CS die), that was purchased from Reifenhäuser REICOFIL GmbH & Co (Germany). This conventional slot MB die has 10 holes/cm and each hole has a diameter of 150 µm. The die tip is sharp and the angle of the air channels was 60° (Figure 1). The nosepiece protruded from the die face by 1 mm and air gap for the air jets was 1 mm.

Figure 3. Dynatec die spin pack and a meltblown sample produced using DT2 die design. The top picture shows a Dynatec spin pack made of five little DT2 dies, 1 inch each. The bottom picture shows a web formed with this spin pack exhibiting some non-uniformity (dark areas correspond to low basis weight while light areas represent high basis weight regions). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Process Conditions

Commercially available metallocene isotactic polypropylene (Achieve^{TM} 6936G) with 1500 melt flow rate (MFR) was purchased from ExxonMobil Chemicals. This resin is the most common polypropylene used for the production of meltblown fabrics because it is easy to spin and requires lower operating pressures. Achieve 6936G PP has a number average molecular weight of 25 kDa and a weight average molecular weight of 60,000 kDa.[25] We ran two trials: one to study the effect of the air aspirator pressure, and the other one to study the effect of the polymer throughput on the fiber and web characteristics. For both trials we kept the air temperature at 553 K (280°C), polymer temperature at 528 K (255°C), basis weight or weight per unit area (also referred to as GSM in some literature), at 20 g/m^2 and the die to collector distance at 13 cm (5 inch). For the first trial we varied the air aspirator pressure between 1.36 and 2.38 bar (i.e., 20 and 35 psi, respectively) and kept the polymer throughput at 0.2 g/hole/min. For the second trial we varied the polymer throughput between 0.05 and 0.2 g/hole/min, and we kept the air aspirator pressure at 1.7 bar (25 psia).

Fiber Diameter Measurements

To examine the fiber morphology and measure the fiber size, samples were sputter coated with a thin layer of gold and analyzed with a scanning electron microscope (SEM, FEI XL-30, FEI Co.). Images were taken between 1000× and 5000× at 5 kV accelerating voltage for the electron beams. Fiber diameters were measured using Image J software. For each meltblown mat, at least 100 individual fiber diameters were measured, and the average fiber diameter and standard deviation are reported herein.

Filtration Efficiency Measurements

Filtration is one of the important applications of meltblown nonwovens as about 50% of the total produced meltblown is consumed in this market.[26] The filtration efficiency of the produced meltblown fibrous mats were examined by using the Automated Filter Tester, TSI 3160, that measures particle penetration versus particle size at a certain aerosol flow rate or face velocity.[27] For each sample, filtration efficiency was measured in triplicates and the average value reported. The filtration efficiency was measured by using dioctylphtalate (DOP) aerosol at a face velocity of 5.33 cm/sec which is the most common or standard face velocity.

Pore Size Measurements

Pore size is another important property of meltblown fabrics. Capillary flow porometery from Porous Materials Inc. (PMI, Ithaca NY) was used to analyze the pore structure of the fabricated meltblown nonwovens. PMI porometry is based on the displacement of a wetting liquid, such as Silwick, from a pore by a gas. The work done by the gas equals the interfacial increase in the free energy. Our samples were tested with the Silwick wetting liquid that had a surface tension of 20.1 dynes/cm. It was assumed that Silwick completely wetted out the samples tested and hence a contact angle of 0°C was taken for calculations of pore diameter using the Young–Laplace equation:[28,29]

$$D = \frac{4\gamma_{L/G} \cdot \cos\theta}{p}$$

where p is the extrusion pressure in MPa, D is the pore diameter in μm, $\gamma_{L/G}$ is the surface tension of the Silwick wetting agent in N/m, and θ is the contact angle of Silwick with the sample, in degrees. This technique is capable of providing us with the average pore diameter, pore diameter at the most constricted part of the pore, and the bubble point diameter which is the largest pore diameter plus the pore diameter distribution.[28,29]

RESULTS AND DISCUSSIONS

Our initial experiments used the parallel plate die DT2. We compared the fiber diameter obtained using this die to meltblown fibers that were produced using the conventional slot (CS) die at the same processing conditions. As observed from Figure 4, the fiber diameter of the meltblown media fabricated using the DT2 are relatively large compared with the conventional meltblown media. The average fiber diameter produced using DT2 at different aspirator pressure varies between 17 and 25 µm, while that for the fibers produced using the CS die at the same conditions varies between 2.5 and 3.5 µm. From our initial observations on the DT2 die performance and the spin pack that we have, we however realized that for the same air aspirator pressure, the amount of air throughput flowing through the DT2 die at the same pressure is significantly lower. For example at 1.7 bars, we had an air throughput of 1.05 m^3/min measured at standard temperature and pressure (STP: 0°C and 14.7 psi) for the CS die, but only 0.33 m^3/min at STP for the DT2 die. This may be due to the limited number of air hoses that are connected to the spin pack of the DT2, one versus four, connected to the spin pack of the CS die. Other reasons for lower fiber attenuation could be the limited number of air nozzles around the polymer nozzle and the protrusion of the spinnerets below the die face. We therefore modified the die block and drilled another hole into it, to accommodate one more air inlet to the air chamber, and we coupled two air hoses and attached them to one of the two air inlets to the Dynatec spin pack (referred to as modified DT2 henceforth). We also obtained another parallel plate MB die design from Dynatc (DT4). The new DT4 die design has a higher number of air nozzles around the polymer nozzles and the polymer spinnerets are flush mounted at the same level as the die face.

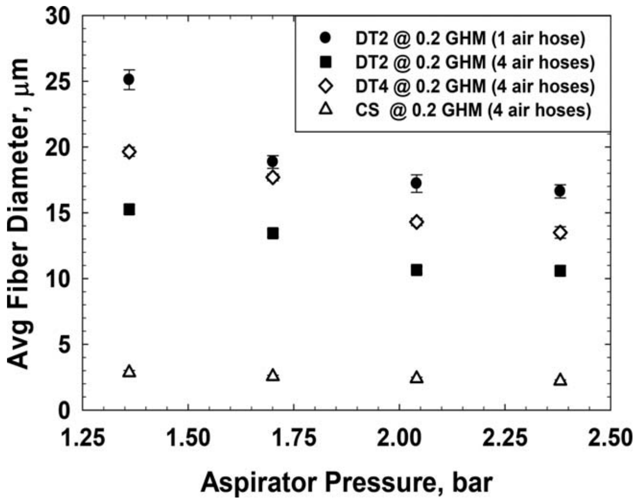

Figure 4. Average fiber diameter for meltblown samples produced by the modified and original DT2 dies, and DT4 and CS dies.

Figure 4 shows the average fiber diameter for the meltblown media produced using the new Dynatec dies (DT4) and the original DT2 after modifying the spin pack to allow for four air hoses to be connected to it. The modified DT2 was able to reduce the fiber size from 25 to 15 µm by increasing the amount of air flowing through the spin pack at the same air aspirator pressure. The air throughput increased from 0.33 to 0.57 m^3/min measured at STP for the 1.7 bar condition because we decreased the spin pack air resistance by increasing the air inlet cross sectional area. This increase in air throughput increased the air velocity and drag force leading to increased fiber attenuation. Results using the DT4 die showed larger fiber diameter compared with the modified DT2 when we ran them

Table I. Air Flowrate through Different Die Designs

	Air throughput (m^3/min @ STP)		
Aspirator pressure (bar)	Conventional slot	Dynatec-2	Dynatec-4
1.02	0.88	0.35	0.31
1.36	0.98	0.50	0.37
1.70	1.05	0.57	0.42
2.04	1.15	0.62	0.45
2.38	1.25	0.68	0.50
2.72	1.31	0.71	0.57
3.40	1.39	0.74	0.59
4.76	1.51	0.82	0.65

at the same conditions. The reason behind the poor performance of DT4 compared with the modified DT2 is that increasing the number of air nozzles around each polymer nozzle from two to four has increased the cross sectional area, and the air throughput was even lower at the same aspirator pressure because of the higher internal air resistance of the new design, (Table I). Therefore, we obtained lower air velocities around the polymer streams that decreased fiber attenuation. Although we had modified the spin pack to accommodate four air hoses like the CS spin pack, the fiber size of the CS die is much smaller because of the high air throughput that can flow through the die at the same air aspirator pressure. We believe that the DT dies have in general a high internal resistance to air flow. This may be suitable for adhesive MB because they need large fiber diameter, but for fabricating meltblown fibers that have typically small fiber diameter, the die design needs to be modified to allow for more air to flow through its air channels. Figure 5 shows the effect of polymer throughput on fiber size, while maintaining air aspirator pressure constant at different values, 1.7, 3.4, or 4.7 bars. As shown, by decreasing polymer throughput and increasing the air aspirator pressure, we reduced the fiber size down to 3–5 μm for the modified DT2 die design, but the CS die still outperformed it because of the reasons explained earlier.

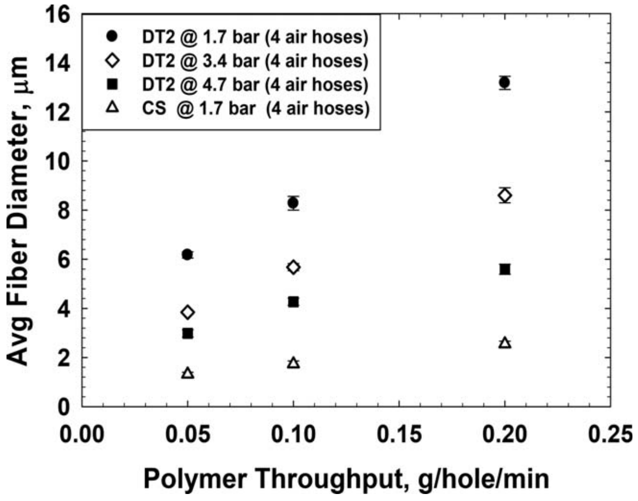

Figure 5. Average fiber diameter for meltblown samples produced at different polymer throughputs.

Figure 6 shows some SEM images for different fabricated meltblown mats using the two die technologies. The first two images [Figure 6(a,b)] are comparing media produced using modified DT2 and CS dies. As depicted, the modified DT2 die was able to produce good quality fibers but their size was approximately five times larger than that fabricated using the conventional slot MB die at the same operating conditions. The second two images (c and d) compare media produced using Dynatec modified DT2 and DT4 die technology at the same conditions. As shown, the sample fabricated using DT4 die has large broken fiber with necking resembling beads. We noticed also that the fabric surface is rough due to such beads and necking; in addition the fiber mat is brittle. Such fabric properties are mainly due to the low drag force that did not cause enough fiber attenuation on the spun polymer filaments. The last two images (e and f) are for samples produced using the modified DT2 at different aspirator pressures. The sample produced at the higher air aspirator pressure shows smaller fiber size because of the higher air velocity that increased fiber attenuation. We also noticed some small spherical beads which is a common defect of meltblown fabrics known as “shot.” Such defect occurs primarily from excessively high temperatures/air velocity or from using too low a polymer molecular weight.

Figure 7 shows the average pore size of the produced meltblowns at different polymer throughputs. We found the pore size of the conventional meltblown media to be much smaller and between 10 and 18 μm, whereas the pore size of the modified DT2 meltblown media are large and between 20 and 60 μm. Typical meltblown nonwovens have average pore size between 5 and 50 μm depending on the fiber diameter and the web basis weight or the web solidity.[1] The large pore size of the modified DT2 meltblowns is a reflection of their large fiber diameters. At 0.05 g/hole/min the pore size of the modified DT2 fabric is three times the pore size of the CS meltblown fabric produced at the same conditions, but pore size was decreased by increasing the air aspirator pressure.

Filtration efficiency is a key factor in quantifying meltblown properties. Typical filtration efficiency of meltblown fabrics is between 20% and 60% depending on fiber diameter and web solidity, but it can be increased to above 99% if they are electrically charged to increase the capturing efficiency.[30–32] Figure 8(a) shows the filtration efficiency for meltblown fibers produced using the modified DT2 and the conventional MB dies at the same conditions. All tested webs have the same basis weight, which were 20 g/m^2. Filtration efficiency of the CS meltblowns was 1.5–2 times the filtration efficiency of the DT2 meltblowns produced at the same air pressure. Figure 8(b) shows the filtration efficiency of the fabricated meltblowns at different polymer throughput. As polymer throughput decreases, filtration efficiency increases because of the smaller fiber diameter that was fabricated. We also notice that the ratio of the efficiency of the MB fabrics of the conventional die to the filtration efficiency of the MB fabrics of the modified DT2 die increases with decreasing polymer throughput. This is mainly due to the significant

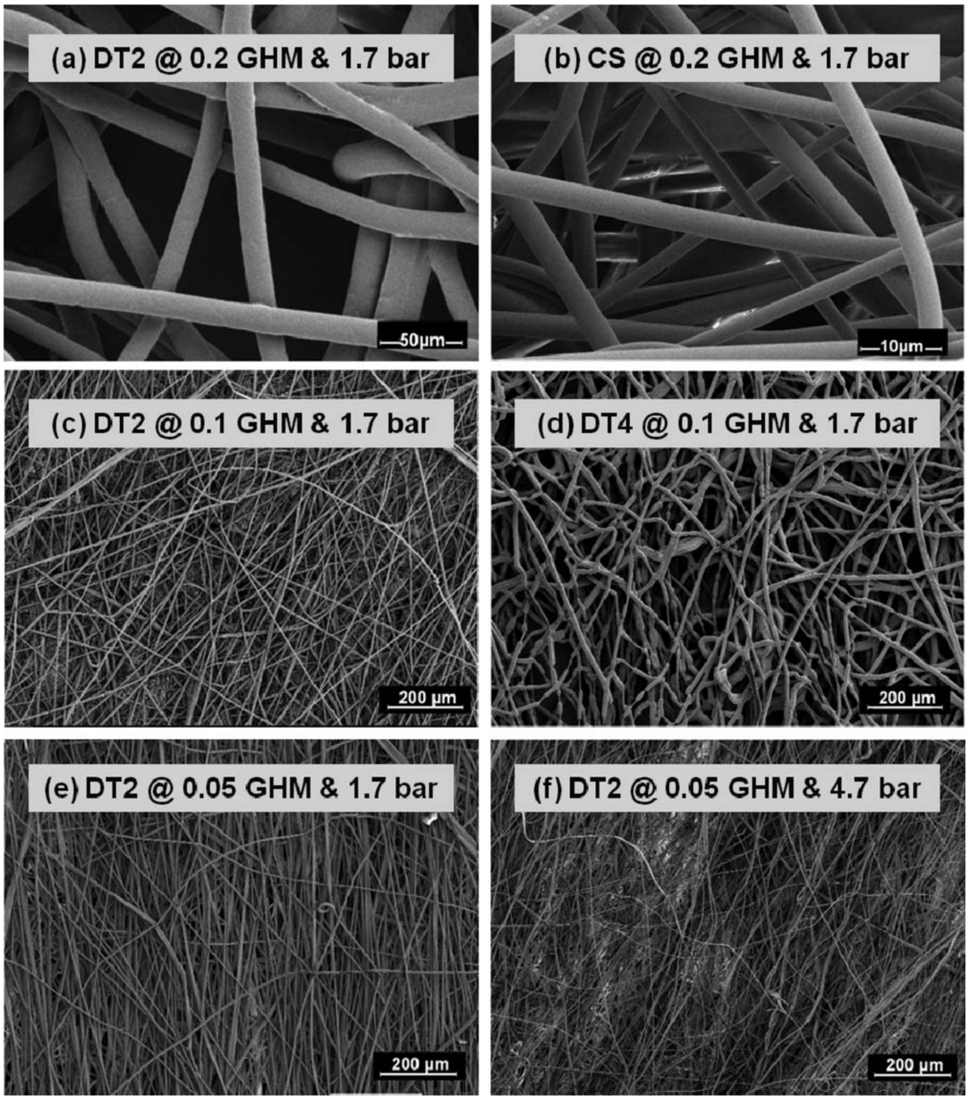

Figure 6. SEM images produced for different die designs (modified DT2, DT4, and CS) at different process conditions. Different magnifications vis a vis scale bars are used for images **a** and **b**.

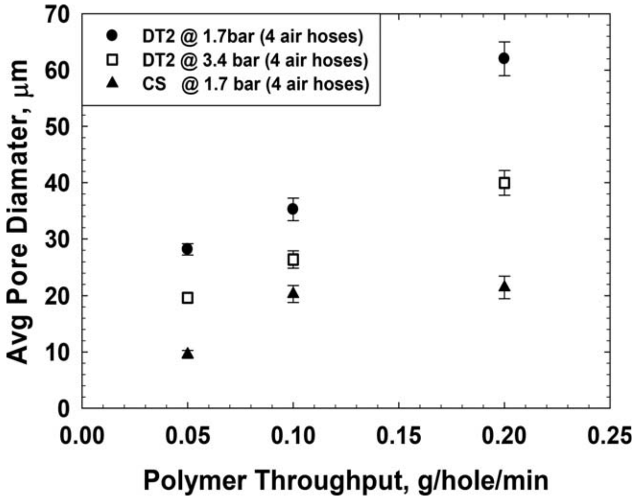

Figure 7. Average pore diameter for meltblown samples produced by modified DT2 and CS dies at different polymer throughputs.

reduction in fiber diameter for the conventional die because of the higher air throughput that impinges on the polymer streams. We did not see the need to examine the filtration performance of the meltblowns produced using DT4 die given that they were brittle and had much bigger fibers containing bead defects and necking.

Generally, the parallel plate die concept could be used to fabricate fibrous filtration media, but with larger fiber size in the range of 5–40 μm. There are several reasons behind this large fiber size; the first one is the high internal resistance to air flow that reduces the air velocity, which is the main parameter affecting fiber attenuation. The second one is the parallel flow nature of the attenuating air. Krutka *et al.*[13] showed that inclined air jets with angle between 30° and 60° will have a pronounced effect on centerline air velocity and temperature that will significantly affect the fiber attenuation and reduce fiber diameter. The third reason is the polymer spinneret position relative to the die face and the air nozzles. In the DT2, original and

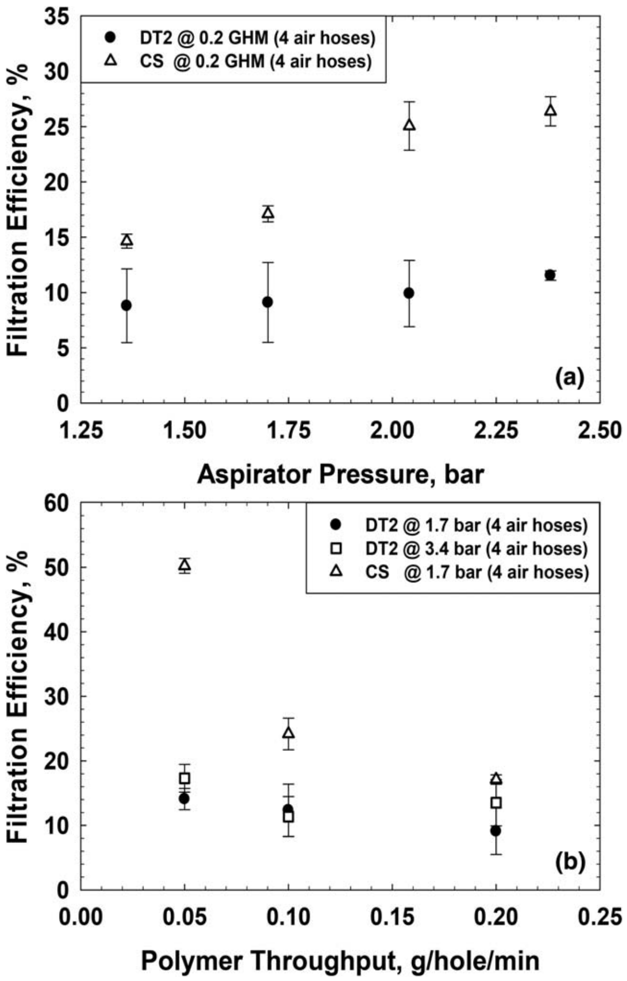

Figure 8. Filtration efficiency for meltblown samples produced by modified DT2 and CS dies at (**a**) different aspirator pressures and (**b**) different polymer throughputs.

modified, the polymer spinnerets protruded from the die face. This protrusion significantly decreases the centerline air velocity and fiber attenuation. Krutka *et al.*[14] used CFD to simulate different MB die configurations, and found that increasing the polymer nozzles recession above the die face leads to an increase in the maximum centerline velocity and the air velocity at the highest tested recession was three times the air velocity for a die with polymer nozzles at the same level with the air nozzles. The significant increase in the maximum centerline air velocity in the z-direction would lead to an increased rate of fiber attenuation for a given air flowrate and thus finer fibers. Aside from the fiber diameter size, we also noticed also that the fabricated webs using the DT dies have poor uniformity, (Figure 3). This is mainly due to the fact that the 15 cm long spinning pack was assembled from six little dies, and we had some spaces between each die with no polymer nozzles. We can avoid this in production if the die is manufactured in a longer length or if we have multiple spinning beams to decrease the non-uniformities. In addition, we noticed that the MB DT2 die system has a lower mat production rate than the conventional slot MB die system. This is mainly due to lower nozzle density in these dies. The polymer nozzle density in a conventional MB die is between 10 and 20 nozzle/cm, while in the DT2 it is between 3 and 7.5 nozzle/cm. This low nozzle density will decrease the overall mass production per unit length of the MB line. To overcome this, we may need to have multiple spinning beams.

SUMMARY

In this study we compared the performance of a new MB die technology to that of the conventional slot MB die technology. The new parallel plate MB die is simple in design with a cost only one-tenth of the conventional MB die. Experimental results showed that this new die configuration with in-house modification could be used to fabricate meltblown fibrous media in the range of 3–10 μm by modulating the process conditions. However, conventional slot MB die produced fibers that were three to five time smaller than what can be produced using the parallel plate MB die design at similar process conditions. The meltblown media produced with the CS MB die achieved 1.5–3 times smaller pore size and showed 1.5-2 times higher filtration efficiency. These results taken together indicate further modification needs to be implemented to the parallel plate MB die to bring it in line with its CS analog. We discussed some design modifications that could potentially enhance the parallel plate MB die performance such as decreasing the internal die resistance to air flow to increase air velocity, increasing the number of air nozzles around the polymer nozzles, recessing the polymer spinnerets above the die face, and having inclined air channels to increase the drag force and fiber attenuation.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the Nowovens Institute (NWI) of North Carolina State University for supporting this research. They would also like to thank Dr Michael Budai (ITW Dynatec) for his donation of the parallel plate MB dies and their support during the course of this study.

REFERENCES

1. Hassan, M. A.; Yeom, B.; Wilkie, A.; Pourdeyhimi, B.; Khan, S. A. *J. Membr. Sci.* **2013**, *427*, 336.
2. Ellison, C. J.; Phatak, A.; Giles, D. W.; Macosko, C. W.; Bates, F. S. *Polymer* **2007**, *48*, 3306.
3. Lee, Y.; Wadsworth, L. C. *Polymer* **1992**, *33*, 1200.
4. Shambaugh, R. L. *Ind. Eng. Chem. Res.* **1988**, *27*, 2363.
5. Schwarz, E. C. A. U.S. Pat. 4,380,570 **1983**.
6. Zhao, R. *Int. Nonwoven J.* **2005**, *14*, 2.
7. Kwok, K. C. U.S. Pat. 5,902,540, **1999**.
8. Kwok, K. C.; Bolyard, E. W.; Riggan, L. E. U.S. Pat. 6,680,021 B1, **2004**.
9. McNally, E. K. *Tappi J.* **1998**, *81*, 193.
10. Tate, B. D.; Shambaugh, R. L. *Ind. Eng. Chem. Res.* **1998**, *37*, 3772.
11. Harpham, A. S.; Shambaugh, R. L. *Ind. Eng. Chem. Res.* **1996**, *35*, 3776.

12. Harpham, A. S.; Shambaugh, R. L. *Ind. Eng. Chem. Res.* **1999**, *36*, 3937.
13. Krutka, H. M.; Shambaugh, R. L.; Papavassiliou, D. V. *Ind. Eng. Chem. Res.* **2002**, *41*, 5125.
14. Krutka, H. M.; Shambaugh, R. L.; Papavassiliou, D. V. *Ind. Eng. Chem. Res.* **2003**, *42*, 5541.
15. Krutka, H. M.; Shambaugh, R. L.; Papavassiliou, D. V. *Ind. Eng. Chem. Res.* **2004**, *43*, 4199.
16. Krutka, H. M.; Shambaugh, R. L.; Papavassiliou, D. V. *Ind. Eng. Chem. Res.* **2005**, *44*, 8922.
17. Uyttendaele, M. A. J.; Shambaugh, R. L. *AIChE J.* **1990**, *36*, 175.
18. Rao, R. S.; Shambaugh, R. L. *Ind. Eng. Chem. Res.* **1993**, *32*, 3100.
19. Marla, V. T.; Shambaugh, R. L. *Ind. Eng. Chem. Res.* **2003**, *42*, 6993.
20. Marla, V. T.; Shambaugh, R. L. *Ind. Eng. Chem. Res.* **2004**, *43*, 2789.
21. Shambaugh, B. R.; Papavassiliou, D. V.; Shambaugh, R. L. *Ind. Eng. Chem. Res.* **2011**, *50*, 12233.
22. Shambaugh, B. R.; Papavassiliou, D. V.; Shambaugh, R. L. *Ind. Eng. Chem. Res.* **2012**, *51*, 3472.
23. Beyler, C. L.; Hirschler, M. M. In SFPE Handbook of Fire Protection Engineering; Editor-in-chief: P. J. DiNenno, NFPA, Quincy, MA, 2002, 3rd Ed, Chapter 7, pp 111–113.
24. Mengeloglu, F.; Karakus, K. *Sensors* **2008**, *8*, 500.
25. Datta, S.; Fu Tse, M.; Sahnoune, A.; Sims, C.; Coffey, J. U.S. Pat. US8052822 B2, **2011**.
26. Butler, I. Innovation Takes Root (ITR) Conference, **2012**.
27. Automated Filter Tester Model TSI 3160, Operation and Service Manual, **2002**.
28. Jena, A.; Gupta, K. *Fluid Part. Sep. J.* **2002**, *14*, 227.
29. Jena, A.; Gupta, K. *Int. Nonwovens J.* **2003**, *123*, 45.
30. Wang, J.; Kim, S. C.; Pui, D. Y. H. *Aerosol Sci. Technol.* **2008**, *42*, 722.
31. Wang, J.; Kim, S. C.; Pui, D. Y. H. *Aerosol Sci.* **2009**, *39*, 323.
32. Podgórski, A.; Bałazy, A.; Gradoń, L. *Chem. Eng. Sci.* **2006**, *61*, 6804.