Fundamental Study of the Effect of the Fiber Wall Thickness and Inner Diameter on the Structure of Polyamide and Polypropylene Hollow Fibers

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Received 18 April 2003; accepted 3 October 2003

ABSTRACT: Some properties of the structure of polyamide (PA) and polypropylene (PP) hollow fibers were investigated in a theoretical fashion. These fibers were simultaneously compared with solid fibers. The structural indices of the hollow fibers, that is, the wall thickness and inner diameter, were systematically examined with the aim of determining their effect on the four conventional structural indices suitable for hollow fibers and for solid fibers. The fiber outer diameter and fiber outer lateral area were examined as well, and the ratio of the fiber outer lateral area to the fiber whole volume and the ratio of this area to the fiber mass were considered. Under assumptions about the fixed level and equal values of the linear density of PA and PP fibers, comments on the aforementioned effect were presented. The structural properties of these fibers with different wall thicknesses and inner diameters were examined.
 J Appl Polym Sci 92: 2017–2022, 2004

Key words: fibers; structure; polyamides; poly(propylene) (PP)

INTRODUCTION

In recent years, considerable changes have taken place in the development of various structural modifications of fibers. There can be no doubt that among these textile products, hollow fibers may be mentioned as good examples. The structure of hollow fibers differs rather significantly from the structure of fibers without longitudinal voids. Additionally, the fiber density (ρ) can be mentioned. For instance, polyamide (PA) and polypropylene (PP) hollow fibers differ in their diameter and surface area properties because of differences in ρ.

Because of their unique structure, hollow fibers have been used in rather different fields of general textile use and in special-purpose products. Hollow fibers have profitable properties for some applications because of their large surface/volume ratio.[1] Hollow fibers enable heat transfer, the cleaning and separation of various liquids and gases, higher moisture absorption and adsorption, and so forth.[1–9] For instance, hollow fibers are suitable in devices that are used for blood purification.[2] One reported technique has been applied to the removal of residual organic solvents in the purification of industrial wastewater.[5] The heat and moisture transport properties of hollow-fiber products are better than those of conventional-structure fibers.[2] Therefore, hollow-fiber garments such as sleeping bags are most efficient because of their vapor permeability and weight. Ultrafine hollow fibers have been used for materials that are light, comfortable to wear, mild and dry, and highly water-repellent.[10] Dye- and metal-chelated microporous PA hollow fibers have a higher human serum albumin adsorption capacity.[3]

A solid, round cross section is the standard shape for most synthetic fibers. The hollow cross section has at least one hollow void enclosed within the fiber and running the entire length of the fiber. Usually, hollow fibers are compared with solid fibers in some respects. On the one hand, the principles that are applied to the spinning of solid fibers are also applied to the manufacturing of hollow fibers. On the other hand, hollow fibers are manufactured with spinnerets of special construction. These spinnerets have segmented orifices with open slits.[1] They must be able to form hollow spaces within the fibers. These hollow fibers often have fiber cross sections and longitudinal voids of different shapes. For example, round, triangular, and quadratic voids are available for these products. Also, several longitudinal voids may be formed[10,11] in hollow fibers. Moreover, it is sometimes important to obtain an excellent uniform geometrical size in the cross section of a fiber. In this case, the spinnerets with tube-in-orifices are used.[1] Additionally, hollow fibers with fins and with an uneven cross-sectional area can be obtained. Therefore, a wall of these fibers can have a uniform or nonuniform thickness.

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Journal of Applied Polymer Science, Vol. 92, 2017–2022 (2004)

Some reseachers[12] are of the opinion that an additional dimensional variable for the spinning of hollow fibers is the inner radius. Such specific structural indices as the fiber wall thickness and fiber inner diameter are used only for hollow fibers. Moreover, a post-treatment of hollow fibers and solid fibers is necessary in different forms, such as drawing, heat treatment, dissolving, coating, and dye modification.[1,3,6,13–15] These processes for manufacturing hollow fibers are more extensive and more complicated than for manufacturing solid fibers.[1] For instance, to form a porous structure in the wall of a hollow carbon fiber, researchers investigated the influence of the oxidation of polyacrylonitrile hollow fibers at different temperatures and durations.[15]

Despite the importance of the structural properties of hollow fibers, the laws and relationships between structural indices have scarcely been described.

Among the numerous publication concerning hollow fibers, only a small number of theoretical investigations could be found. A noteworthy theoretical work was reported by Gupta.[16] In this work, the change in the hollow-fiber weight in comparison with that of a cylindrical compact fiber with the same outer diameter was investigated through calculations. On the basis of Gupta's results, we have found that the ratio of the inner diameter to the outer diameter of a hollow fiber significantly affects the weight of the fiber. Others, researching the integration of microsystems in hollow-fiber-reinforced composites, presented a relationship between capillarity and fiber geometry.[17] According to theoretical data on their website, capillarity is the highest for hollow fibers with the thinnest walls. The effects of spinning variables on the hollow portions of fibers were previously studied with a finite element method.[12,18]

Other reports have been based on experimental investigations. For instance, PA hollow-fiber cross sections and the outer layer morphology have been observed after dye modification.[14] Some experimental results for hole formation during a melt-spinning process have been reported.[19] Some researchers have investigated the hollowness of fibers in a continuous drawing process.[13] Comments on the experimental values of the fiber wall thickness have been presented elsewhere.[1,20–24] Indices such as the fiber inner diameter have been mentioned in the literature.[1,15,21–27] This index for different types of hollow fibers may be 0.01 μm[27] but is sometimes greater than 4000 μm.[22] PP hollow fibers with an inner diameter of 200 μm are used in membrane bioreactors for the denitrification of contaminated drinking water.[24] Other undrawn samples of hollow fibers used for filtration have an inner diameter of approximately 165 μm.[1] The structure of hollow fibers with an inner diameter of 300 μm has been previously examined.[15] The diameter of the hollow core of fibers used in a laser apparatus is 700 μm.[26]

TABLE I
Structural Indices

Abbreviation	Meaning
b_f	Hollow-fiber wall thickness (μm)
d_f	Solid-fiber diameter (μm)
d_{fi}	Hollow-fiber inner diameter (μm)
d_{fo}	Hollow-fiber outer diameter (μm)
l	Fiber length (m)
ρ	Fiber density (mg/m^3)
S_f	Solid-fiber outer lateral area (μm^2 10^6)
S_{fh}	Hollow-fiber outer lateral area (μm^2 10^6)
s_m	Ratio of the solid-fiber lateral area to the solid-fiber mass (μm^2 g^{-1} 10^{10})
s_{mh}	Ratio of the hollow-fiber outer lateral area to the hollow-fiber mass (μm^2 g^{-1} 10^{10})
s_v	Ratio of the solid-fiber lateral area to the solid-fiber volume (μm^{-1} 10^{-3})
s_{vh}	Ratio of the hollow-fiber outer lateral area to the hollow-fiber whole volume (μm^{-1} 10^{-3})
T_f	Solid-fiber linear density (dtex)
T_{fh}	Hollow-fiber linear density (dtex)

Theoretical relationships for the control of hollow-fiber geometry show the technological possibility of adjusting the fiber wall thickness independently of the fiber outer diameter.[20] Therefore, it is also possible to manufacture hollow fibers with rather different wall thicknesses and fiber inner diameters. For instance, two different ranges for the inner diameter and wall thickness of hollow fibers have been reported in a patent.[21] The one range for this diameter is 100–300 μm. The wall thickness of these fibers varies from 3 to 20 μm. Another range of the inner diameter is 150–200 μm. These samples have wall thicknesses of 5–8 μm. Similar data for the inner diameter (200 μm) and wall thickness (25 μm) have been presented in another patent.[23] The hollowness (percentage of voids in a cross section) of some melt-spun PP samples was reported to range from 0 to 69%.[28] The thickness of a porous wall of a hollow fiber was reported to be greater than 100 μm.[22] Hollow fibers with a wall thickness of less than 100 μm have been mentioned.[29]

This review demonstrates the rather wide variety of data available for specific structural indices of hollow fibers. The influence of these indices on conventional structural indices has not been examined in a theoretical fashion yet. Here we propose the necessary relations and examine this influence.

EXPERIMENTAL

Structural indices were used, and the meaning of each index fir the PA and PP fibers is given in Table I. One series of indices [hollow-fiber linear density (T_{fh}), hollow-fiber outer diameter (d_{fo}), hollow-fiber outer lat-

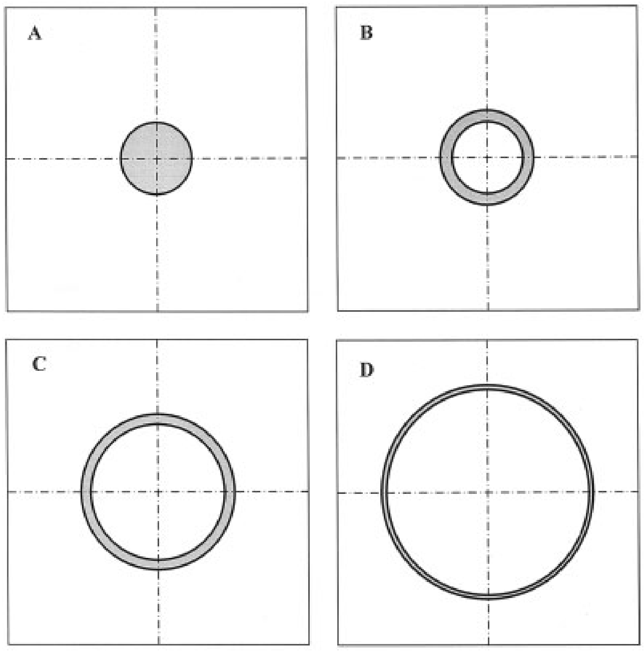


Figure 1 Schemes of cross-sectional samples of fibers with a constant linear density: (A) solid fiber and (B–D) hollow fibers.

eral area (S_{fh}), ratio of the hollow-fiber outer lateral area to the hollow-fiber whole volume (s_{vh}), and ratio of the hollow-fiber outer lateral area to the hollow-fiber mass (s_{mh})] was used to describe the structure of hollow fibers. Usually, solid fibers can be described by means of analogous indices [solid-fiber linear density (T_f), solid-fiber diameter (d_f), solid-fiber outer lateral area (S_f), ratio of the solid-fiber lateral area to the solid-fiber volume (s_v), and ratio of the solid-fiber lateral area to the solid-fiber mass (s_m)]. Therefore, T_{fh}, d_{fo}, S_{fh}, s_{vh}, and s_{mh}, because of their universality, are named conventional structural indices.

This research is based on proposed relations between these indices and two specific indices mentioned earlier: the hollow-fiber wall thickness (b_f) and the hollow-fiber inner diameter (d_{fi}). The methodology of this research uses the following preconditions: indices b_f and d_{fi} are variables; indices T_{fh} and T_f remain at a fixed level, being independent of the variation of indices b_f and d_{fi} (i.e., $T_{fh} = T_f$ = constant); and indices T_{fh} and T_f have equal values for PA and PP fibers.

In other words, we considered the hollow and solid fibers with a constant polymer cross-sectional area. This approach means that the polymer throughput is constant and that the take-up velocity is constant for each sample. As shown in Figure 1, the four cross-sectional samples of these fibers were labeled A, B, C, and D. Index d_{fi} varied for these samples as follows: $d_{fi} = 0$, $d_{fi} = d_f$, $d_{fi} = 2d_f$, and $d_{fi} = 3d_f$, respectively. The following values of b_f were used: for sample A, $b_f = 0.5000d_f$; for sample B, $b_f = 0.2070d_f$; for sample C, $b_f = 0.1181d_f$; and for sample D, $b_f = 0.0812d_f$. One series of computations was made for PA hollow fibers with a constant linear density of 39 dtex. For example, hollow fibers with such linear density are produced by Kanebo Co. (Tokyo, Japan).[26] Another series was presented for PP hollow fibers with the same linear density. ρ was 1.14 Mg/m^3 for PA fibers and 0.91 Mg/m^3 for PP fibers. The fiber length (l) was 1 m for all the samples in this study.

RESULTS AND DISCUSSION

Math model

All the relations examined in this article are suitable for round hollow fibers with a round, concentric hollow space inside the cross section.

T_{fh} and T_f are defined as follows:

$$T_{fh} = \frac{\pi(d_{fo}^2 - d_{fi}^2)\rho}{4} \quad (1)$$

$$T_f = \frac{\pi d_f^2 \rho}{4} \quad (2)$$

With the precondition $T_{fh} = T_f$ = constant, we find that

$$d_{fo}^2 - d_{fi}^2 = d_f^2 \quad (3)$$

or

$$d_{fo} = (d_f^2 + d_{fi}^2)^{1/2} \quad (4)$$

Equation (4) was used to develop the following relation between S_{fh} and d_{fi}:

$$S_{fh} = \pi(d_f^2 + d_{fi}^2)^{1/2} l \quad (5)$$

In a similar manner, eqs. (6) and (7) for s_{vh} and s_{mh} were also proposed:

$$s_{vh} = \frac{4}{(d_f^2 + d_{fi}^2)^{1/2}} \quad (6)$$

$$s_{mh} = \frac{4(d_f^2 + d_{fi}^2)^{1/2}}{d_f^2 \rho} \quad (7)$$

Equation (3) can be written as follows:

$$(d_{fo} - d_{fi})(d_{fo} + d_{fi}) = d_f^2 \quad (8)$$

Because

$$b_f = 0.5(d_{fo} - d_{fi}) \quad (9)$$

we obtain

$$b_f = 0.5\ d_f^2/(d_{fo} + d_{fi}) \quad (10)$$

Substituting the value of d_{fo} from eq. (4) gives

$$b_f = \frac{0.5\ d_f^2}{(d_f^2 + d_{fi}^2)^{1/2} + d_{fi}} \quad (11)$$

Here, if d_{fi} is 0, b_f is $0.5000d_f$; if d_{fi} is equal to d_f, b_f is $0.5d_f/(2^{1/2} + 1) = 0.2070d_f$. If d_{fi} is equal to $2d_f$ then b_f is equal to $0.5d_f/(5^{1/2} + 2) = 0.1181d_f$. If d_{fi} is equal to $3d_f$, b_f is equal to $0.5d_f/(10^{1/2} + 3) = 0.0812d_f$. The application of eqs. (9) and (11) enables us to compute the values of the d_{fo} for any case of b_f. Similarly, indices S_{fh}, s_{vh}, and s_{mh} for hollow fibers, for which b_f fluctuates within the inspected range, have been computed.

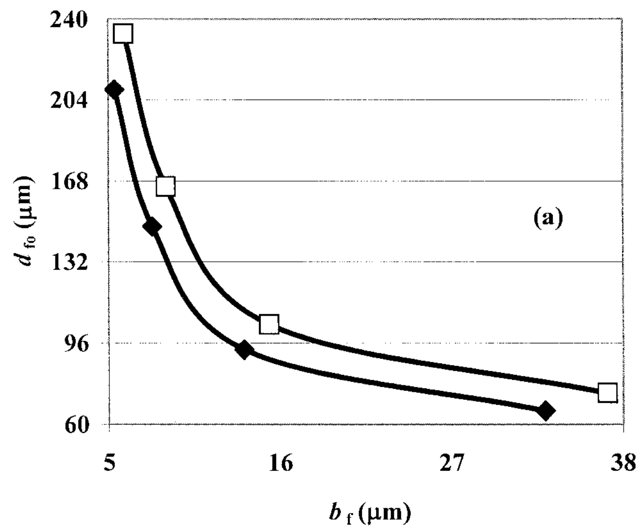
Effect of the wall thickness

The effect of b_f on d_{fo} is shown in Figure 2(a). d_{fo} decreases as b_f increases. We find $d_{fo} = d_f$ for sample A, whereas for samples B–D, the condition $d_{fo} > d_f$ holds. For instance, the calculations for PA and PP hollow-fiber samples B show that index d_{fo} is higher by 41% than that of solid samples A. Moreover, the values of the d_{fo} are greater for PP fibers than for PA fibers. These values differ by approximately 12%.

The tendencies for the relations between b_f and S_{fh}, presented in Figure 2(b), are similar to the situation described earlier for index d_{fo}. A linear relation between index d_{fo} and index S_{fh} determines the similarity between these graphs.

A different effect is obtained for index s_{vh} and index s_{mh}, as shown in Figure 3(a,b), respectively. When b_f increases, s_{vh} has a tendency to increase. Because of this tendency, sample A has the highest value of s_v. The values of s_{vh} for hollow fibers B–D are smaller than that for solid sample A (i.e., $s_{vh} < s_v$). Another situation is determined for index s_{mh}. This index falls if b_f raises. In other words, the condition $s_{mh} > s_m$ indicates this peculiarity.

The contrary tendencies shown in Figure 3(a,b) may be explained as follows. First, the outer lateral area of a hollow fiber increases with less intensity than growth of its whole volume, including the volume of the hollow space. Therefore, the highest value of index s_{vh} [see Fig. 3(a)] was computed for a solid fiber. Second, according to the assumption about the fixed value of index T_{fh}, we also have a fixed value of the hollow-fiber mass. Thus, index s_{mh} has the same tendency of decreasing [see Fig. 3(b)] as indices d_{fo} and S_{fh}. With different values of ρ, index s_{mh} is higher for PP fibers than for PA fibers [Fig. 3(b)], as shown in the graphs for indices d_{fo} and S_{fh} [Fig. 2(a,b)]. Meanwhile, Figure 3(a) shows the reverse tendency on this point. Because of a higher value of ρ, index s_{vh} for PA fibers is always greater than this index for PP fibers. In this case, the values of s_{vh} for PP and PA fibers show a difference of about 12%.



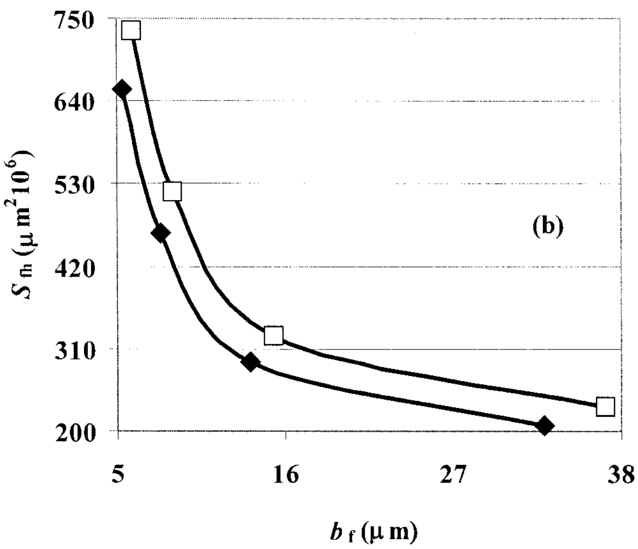


Figure 2 Effect of index b_f on (a) index d_{fo} and (b) index S_{fh} for (◆) PA and (□) PP fibers with a constant linear density.

Effect of the inner diameter

Another series of relations has been computed for the variable d_{fi}. These results are shown for indices d_{fo}, S_{fh}, s_{vh}, and s_{mh} in Figures 4(a,b) and 5(a,b), respectively. Contrary to previous tendencies for factor b_f in Figures 2(a,b) and 3(b), an increase in index d_{fi} causes an increase in indices d_{fo}, S_{fh}, and s_{mh} [Figs. 4(a,b) and 5(b)]. The relations for index s_{vh} [see Fig. 5(a)] also show the reverse character of the previous relations shown in Figure 3(a).

The differences between the structural indices for PA and PP fibers in Figures 4 and 5 are identical to

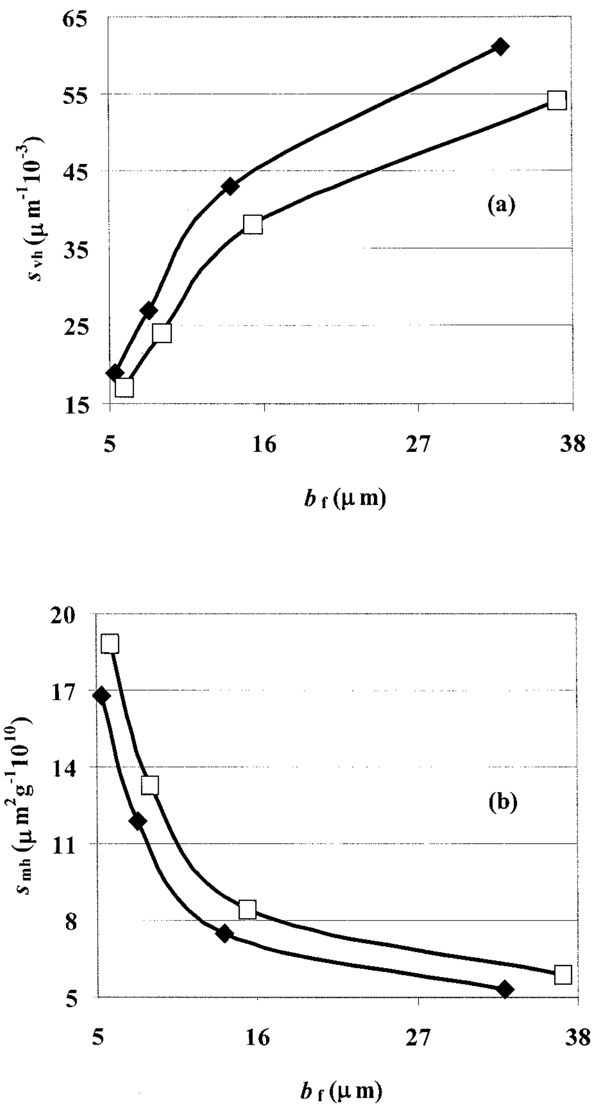


Figure 3 Effect of index b_f on (a) index s_{vh} and (b) index s_{mh} for (♦) PA and (□) PP fibers with a constant linear density.

those previously mentioned for these fibers in Figures 2 and 3. These trends are conditioned by the density difference between PA and PP fibers. Thus, the values of d_{fo}, S_{fh}, and s_{mh} for PP fibers are greater than the values for PA fibers in any case for the fiber inner diameter. Only index s_{vh} is higher for PA samples than for PP fibers.

Application possibilities

Finally, we can observe the practical meaning of the aforementioned relations because the structural indices investigated in this study are closely connected to the possibility of adjusting various properties of new materials produced on the basis of hollow fibers. The results are also applicable to the explanation of various manufacturing processes of textile materials.

The current computations have been carried out for hollow fibers with a constant linear density. Therefore, the proposed relations show different peculiarities in the use of the same value of the material weight in the construction of these fibers. For instance, such indices as the yarn diameter, cover factor, and fabric thickness are greater for hollow fibers. This peculiarity indicates the effect of an increased outer diameter of the fibers. Meanwhile, a large outer lateral area for these fibers shows why the consumption of the size, dyestuff, and other materials is greater than the consumption for conventional fibers. Another example of the process of crystallization in melt-spun fibers may be mentioned. In melt spinning, the fiber cools because of convective transfer with the air. This loss of heat is proportional to the outer lateral area of the fiber. Hence, hollow fibers are quenched more quickly than solid fibers. Index S_{fh} indicates the hollow-fiber outer lateral area;

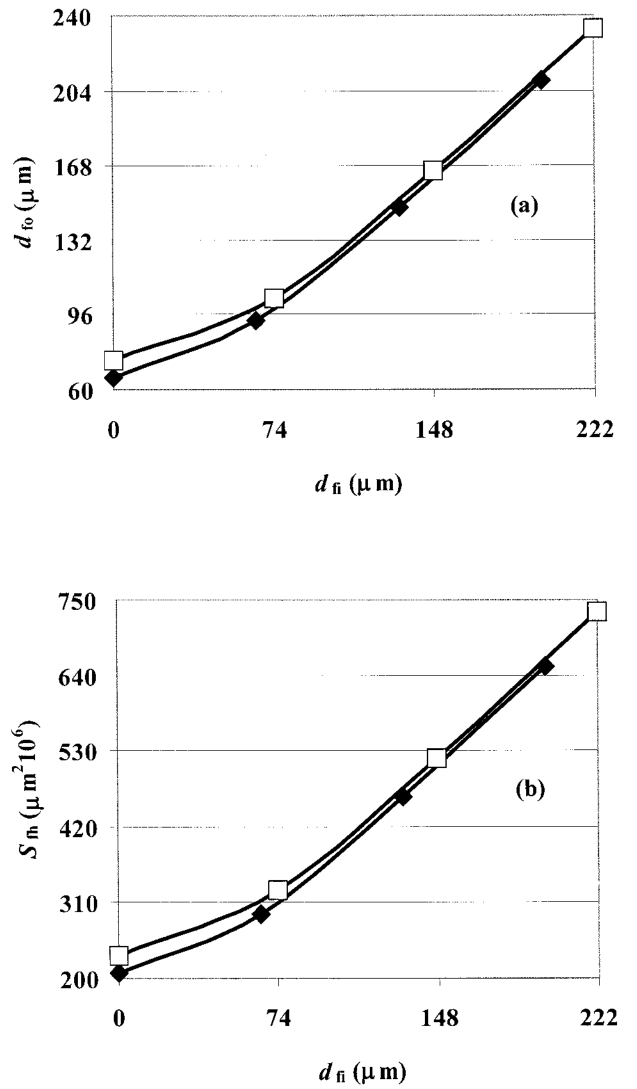


Figure 4 Effect of index d_{fi} on (a) index d_{fo} and (b) index S_{fh} for (♦) PA and (□) PP fibers with a constant linear density.

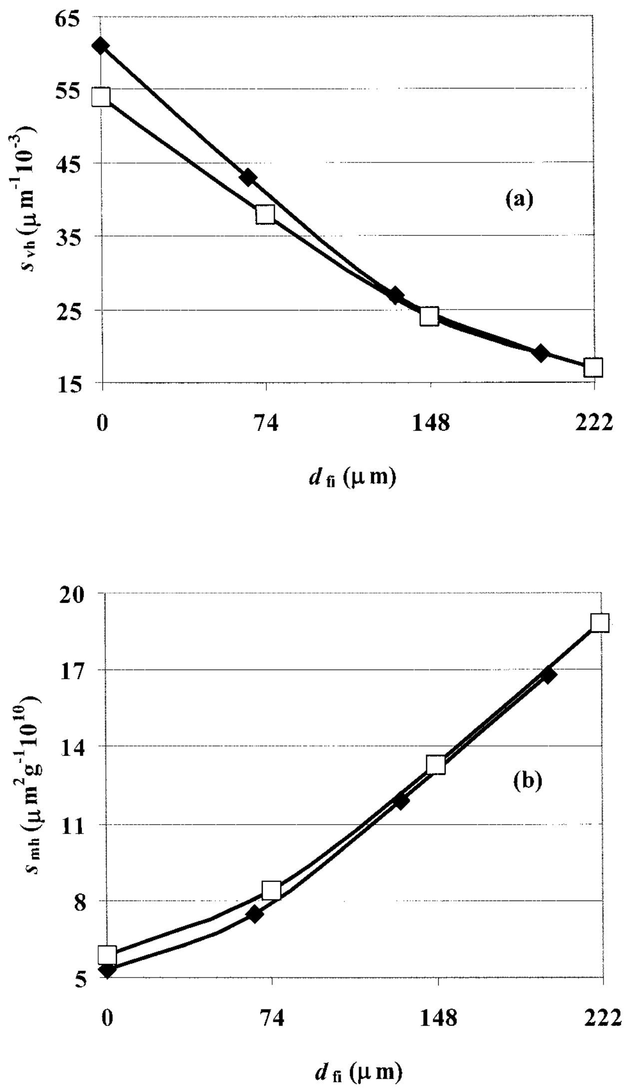


Figure 5 Effect of index d_{fi} on (a) index s_{vh} and (b) index s_{mh} for (◆) PA and (□) PP fibers with a constant linear density.

in this case, we can analyze only the absolute values. Meanwhile, such indices as s_{vh} and s_{mh} are useful if our aim is to compare the properties of hollow fibers with different whole volumes or masses.

CONCLUSIONS

A math model and some theoretical relations for the structural properties of PA and PP hollow fibers with fixed linear densities have been proposed and studied. A comparison of these fibers with solid fibers has also been made.

On the basis of these relations, the following generalizations can be made:

Indices d_{fo}, S_{fh}, and s_{mh} for PP hollow fibers are greater than these indices for PA fibers, whereas the opposite tendency holds for index s_{vh}.

Hollow fibers have higher values of indices d_{fo}, S_{fh}, and s_{mh} than analogous solid fibers; in contrast, index s_{vh} is highest for solid samples.

The greatest values of indices d_{fo}, S_{fh}, and s_{mh} are computed for hollow fibers with the lowest value of index b_f and for samples with the highest value of index d_{fi}.

The highest values of index s_{vh} are characteristics of hollow fibers with the lowest value of index d_{fi} and of products with the highest value of index b_f.

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