

## Theoretical Investigation of Hollow Fibres Structure: Relations between Fibre Inner Diameter, Wall Thickness, and Conventional Structural Indices

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Some theoretical investigations of morphological structure of hollow fibres of the same linear density are developed in the current study. The structural indices of hollow fibres, namely fibre inner diameter and fibre wall thickness are systematically examined to show their relations with four conventional structural indices of fibres. Among these indices a hollow fibre outer diameter and a hollow fibre outer lateral area are used. Also such two indices as a ratio of hollow fibre outer lateral area to hollow fibre whole volume and a ratio of this area to hollow fibre mass are considered. In order to show the main structural peculiarities of the hollow fibres properly, the proposed relations cover a wide range of inner diameter and wall thickness up to the values for solid products. The comments on these relations for polyamide and polypropylene fibres with linear density of 3.9 dtex are presented.

*Keywords:* hollow fibre, fibre inner diameter, fibre structure, fibre wall thickness.

### INTRODUCTION

The innovations of fibres developed to meet the present day requirements are very significant. In recent years, considerable changes have taken place in the development of various morphological modifications of fibres. Among these textile products hollow fibres may be mentioned as a right example.

Through the unique structural peculiarities the hollow fibres became recognised in rather different fields of textile use, also in products of special purposes. Hollow fibres enable us to reduce a heat transfer, to clean various liquids and gases, to obtain higher moisture absorption, etc.

Usually the hollow fibres are compared with solid fibres in some respects. On one side, it is worth to note that principles, which are applied for spinning of solid fibres, are also applied in manufacture of hollow fibres. On the other side, hollow fibres are manufactured by means of the spinnerets of special construction. These spinnerets have segmented orifice with open slits [1]. Such construction must be able to form the hollow space within the fibre. Moreover, sometimes it is important to obtain an excellent uniform geometrical size in the cross-section of the fibre. For this case the spinnerets of the tube-in-orifice type are used [1].

Thus, structure of the hollow fibres significantly differs from a structure of solid fibres. For example, such specific structural indices as fibre inner diameter and fibre wall thickness are used only in a case of hollow fibres.

Moreover, an after-treatment of the hollow fibres as well as of solid fibres is necessary in different forms such as drawing, heat treatment, dissolving, coating, etc [1 – 7]. According to [1], these processes of hollow fibre manufacturing are more extensive and more complicated than those of solid fibres. For instance, after-treatment technologies are carried out sometimes in order to form a porous structure in the wall of the hollow fibre [1, 7].

As a rule, the publications concerning hollow fibres include processing and device patents also the specific technological and application aspects.

Despite the importance of hollow fibres structural properties, the laws and relations between these parameters are scarcely described. Among the numerous references connected with hollow fibres only a small number of theoretical investigations could be found.

A noticeable theoretical work was done by Gupta [8]. The changes of various properties of hollow fibre and comparative analysis with cylindrical compact fibre of the same outer diameter were performed. According to [8], the ratio between inner and outer diameters of hollow fibre significantly influences the weight of this fibre. For instance, the effect of this ratio on mechanical rigidity is smaller as compared with the weight index.

The authors of research project (see Web site [www.imes.ethz.ch](http://www.imes.ethz.ch)) regarding the integration of microsystems in hollow fibre reinforced composites presented a relation between capillarity and fibre geometry. According to this source, the capillarity is higher for hollow fibres with thinner wall.

The other references are based on experimental investigations.

The comments on fibre wall thickness are also presented in [1, 9 – 13]. Such index as fibre inner diameter was mentioned in references [1, 10 – 12, 14]. For instance, the polypropylene hollow fibres with an inner diameter of 200  $\mu\text{m}$  are used in membrane for denitrification of contaminated drinking water [14]. The other undrawn samples of hollow fibres for the purpose of filtration have an inner diameter 165  $\mu\text{m}$  approximately [1]. After spinning of the unoriented fibres a drawing process in several steps is necessary to obtain the desired microporous structure in the fibre wall [1].

Technology in [7] proposes polypropylene hollow fibres with inner diameter ranging from 180 up to 250  $\mu\text{m}$ . These products are used for the purpose of filtration. Diameter of the hollow core of fibres used in laser-apparatus is 700  $\mu\text{m}$  (see information in Web site [www.shinzai.com/fiber2.htm](http://www.shinzai.com/fiber2.htm)). The theoretical relations in

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[9] for the control of hollow fibre geometry show technological possibility to adjust the fibre wall thickness independently of the fibre outer diameter. Therefore it is possible to manufacture the samples of the hollow fibres with rather different wall thickness and fibre inner diameter. For instance, two different ranges of inner diameter and wall thickness of hollow fibres produced on the basis of cellulose solution are indicated in [10]. One range for this diameter is 100 – 300  $\mu\text{m}$ ; the wall thickness of these fibres is between 3 and 20  $\mu\text{m}$  in [10]. The other range of inner diameter varies between 150 and 200  $\mu\text{m}$  [10]. The wall thickness for these samples is 5 to 8  $\mu\text{m}$  [10]. Similar data of inner diameter (200  $\mu\text{m}$ ) and wall thickness (25  $\mu\text{m}$ ) are presented in [12]. Thick polyethylene hollow fibre with inner diameter greater than 4000  $\mu\text{m}$  is proposed in [11]. Thickness of a porous wall of this fibre is more than 100  $\mu\text{m}$  [11].

The above-presented survey shows a rather wide variety of data for specific structural indices of hollow fibres. A question about relations between these indices and the conventional structural indices isn't suggested in a theoretical way as yet.

The current study is focused on the tendencies between some specific structural indices of hollow fibres and their conventional structural indices. The latter indices are suitable for a wide variety of fibre structures. Here such products as the hollow fibres of different inner diameter and wall thickness, even the solid fibres are kept in mind.

## OBJECT OF THE INVESTIGATION AND ASSUMPTIONS

The current investigation is made for polyamide (PA) and polypropylene (PP) fibres. The following structural indices of these fibres used here are:

- $T_{fh}$  - hollow fibre linear density;
- $d_{fo}$  - hollow fibre outer diameter;
- $S_{fh}$  - hollow fibre outer lateral area;
- $s_{vh}$  - ratio of hollow fibre outer lateral area to hollow fibre whole volume;
- $s_{mh}$  - ratio of hollow fibre outer lateral area to hollow fibre mass.

Usually solid fibres may be described by means of analogous indices  $T_f$ ,  $d_f$ ,  $S_f$ ,  $s_v$ , and  $s_m$ . Therefore the previous indices  $T_{fh}$ ,  $d_{fo}$ ,  $S_{fh}$ ,  $s_{vh}$ , and  $s_{mh}$  because of their universality are named as conventional structural indices. In the current paper we investigate the relations between these indices and two earlier mentioned specific indices, i.e., hollow fibre inner diameter  $d_{fi}$  and hollow fibre wall thickness  $b_f$ .

The methodology of the research is based on such assumptions:

- the indices  $d_{fi}$  and  $b_f$  are variables;
- the indices  $T_{fh}$  and  $T_f$  remain at fixed level independently of variation of the indices  $d_{fi}$  and  $b_f$ , i.e.,  $T_{fh} = T_f = \text{const}$ ;
- the indices  $T_{fh}$  and  $T_f$  have equal values for PA and PP fibres.

Index  $d_{fi}$  varied in such order:  $d_{fi} = 0$ ,  $d_{fi} = d_f$ ,  $d_{fi} = 2d_f$  and  $d_{fi} = 3d_f$ , where  $d_f$  - solid fibre diameter.

One series of computations is made for polyamide (PA) hollow fibre with a linear density of 39 dtex. Kanebo (Japan) company (see Web site [www.kanebotx.com](http://www.kanebotx.com)) produces similar hollow fibre. Other series is presented for polypropylene (PP) hollow fibre with the same linear density. The values of fibre density used in this research are the following:  $\rho = 1140 \text{ kg/m}^3$  for PA fibres,  $\rho = 910 \text{ kg/m}^3$  for PP fibres. Fibre length is equal to 1 m for all samples in this study.

It is worth to point out that all the relations examined in this paper are suitable for round hollow fibres with a round concentric hollow space inside cross-section.

## RESULTS AND DISCUSSIONS

### Main equations

Solid fibre linear density  $T_f$  and hollow fibre linear density  $T_{fh}$  are defined as

$$T_f = \frac{\pi d_f^2 \rho}{4}, \quad (1)$$

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

Because of the second assumption, we have:

$$\frac{\pi d_f^2 \rho}{4} = \frac{\pi(d_{fo}^2 - d_{fi}^2)\rho}{4} \quad (3)$$

or

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

From (4), it is easy to express the following relation between hollow fibre outer lateral area  $S_{fh}$  and inner diameter  $d_{fi}$ :

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

where  $l$  is the fibre length.

In a similar manner the equations for the indices  $s_{vh}$  and  $s_{mh}$  we re also proposed:

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

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

The values of wall thickness  $b_f$  varied in accordance with the (4) modified into the following form:

$$b_f = \frac{d_f^2}{2[(d_f^2 + d_{fi}^2)^{1/2} + d_{fi}]}. \quad (8)$$

Here for  $d_{fi} = 0$  we have:  $b_f = \frac{d_f}{2}$ . (9)

In a case of  $d_{fi} = d_f$ :

$$b_f = \frac{d_f}{2(2^{1/2} + 1)}. \quad (10)$$

If  $d_{fi} = 2d_f$  then

$$b_f = \frac{d_f}{2(5^{1/2} + 2)} \quad (11)$$

Using  $d_{fi} = 3d_f$ , the wall thickness becomes

$$b_f = \frac{d_f}{2(10^{1/2} + 3)} \quad (12)$$

One additional equation, which was widely used in this research, is

$$d_{fo} = 2b_f + d_{fi} \quad (13)$$

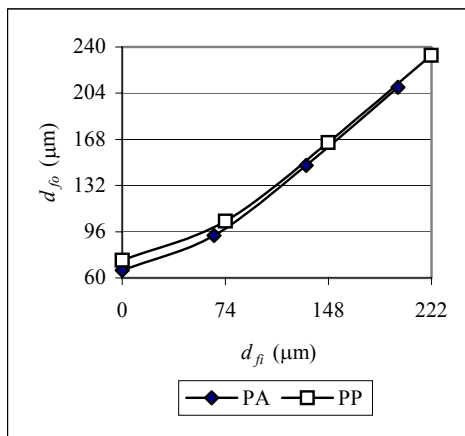
For instance, application of (13) and (8) enables us to compute the values of the hollow fibre outer diameter  $d_{fo}$ :

$$d_{fo} = \frac{d_f^2}{(d_f^2 + d_{fi}^2)^{1/2} + d_{fi}} + d_{fi} \quad (14)$$

Similarly, the indices  $S_{fh}$ ,  $s_{vh}$ , and  $s_{mh}$  for hollow fibres, wall thickness  $b_f$  of which fluctuates at the inspected range, have been computed.

### Graphical representation of relations

A graphical view of the relations between hollow fibre inner diameter  $d_{fi}$  and hollow fibre outer diameter  $d_{fo}$  is shown in Fig. 1. The index  $d_{fo}$  increases as the value of index  $d_{fi}$  grows. Moreover, the values of the index  $d_{fo}$  are higher for PP fibre compared with PA fibre because of difference of the density.

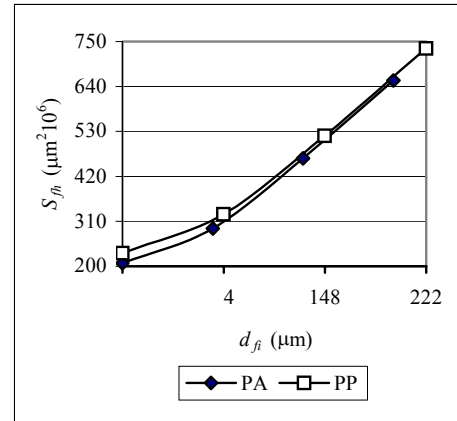


**Fig. 1.** Relations between index  $d_{fi}$  and index  $d_{fo}$ . PA– polyamide fibre, PP – polypropylene fibre

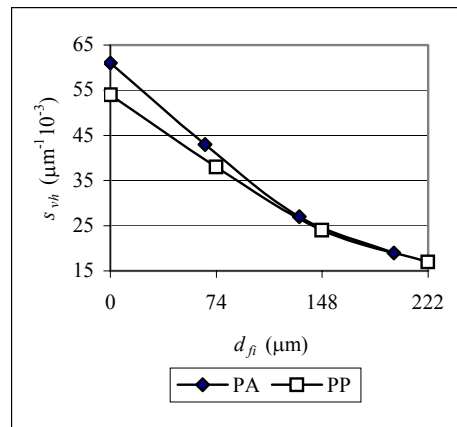
The tendencies for relations between hollow fibre inner diameter  $d_{fi}$  and hollow fibre outer lateral area  $S_{fh}$  presented in Fig. 2 are similar to the situation described earlier for the index  $d_{fo}$ . A linear relation between the index  $d_{fo}$  and the index  $S_{fh}$  determines the similarity between these graphs.

Different types of relations are obtained for the index  $s_{vh}$  (Fig. 3) and index  $s_{mh}$  (Fig. 4). In the case of the increase of the  $d_{fi}$ , the ratio of hollow fibre outer lateral area to hollow fibre whole volume (index  $s_{vh}$ ) has tendency to decrease. Another situation is determined for the index  $s_{mh}$ , i.e., for the ratio of hollow fibre outer lateral area to

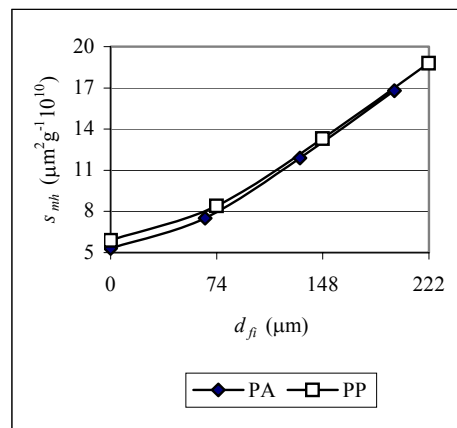
hollow fibre mass. This index increases with the increase of



**Fig. 2.** Relations between index  $d_{fi}$  and index  $S_{fh}$ . PA– polyamide fibre, PP – polypropylene fibre

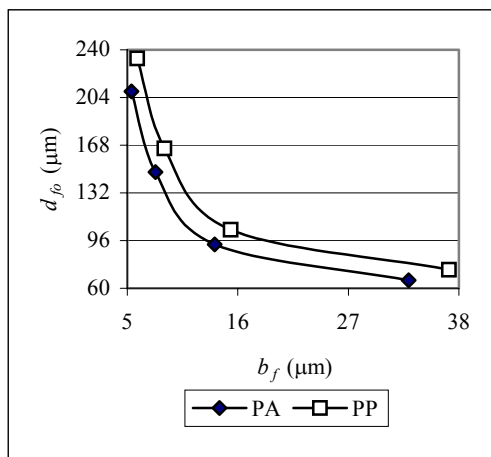


**Fig. 3.** Relations between index  $d_{fi}$  and index  $s_{vh}$ . PA – polyamide fibre, PP – polypropylene fibre

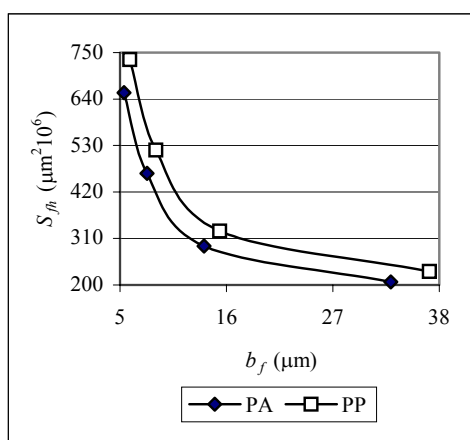


**Fig. 4.** Relations between index  $d_{fi}$  and index  $s_{mh}$ . PA – polyamide fibre, PP – polypropylene fibre

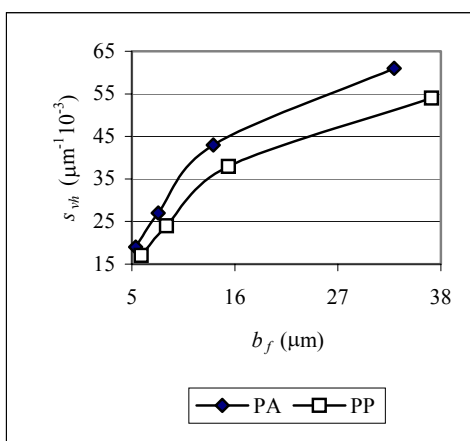
$d_{fi}$ . These contrary tendencies may be explained in such a way. Firstly, the outer lateral area of hollow fibre increases slowly compared with the increase of its whole volume including volume of hollow space. Therefore, the highest index  $s_{vh}$  (see Fig. 3) was computed for a solid fibre. Secondly, according to the assumption about fixed index



**Fig. 5.** Relations between index  $b_f$  and index  $d_{fo}$ . PA – polyamide fibre, PP – polypropylene fibre



**Fig. 6.** Relations between index  $b_f$  and index  $S_{fh}$ . PA – polyamide fibre, PP – polypropylene fibre

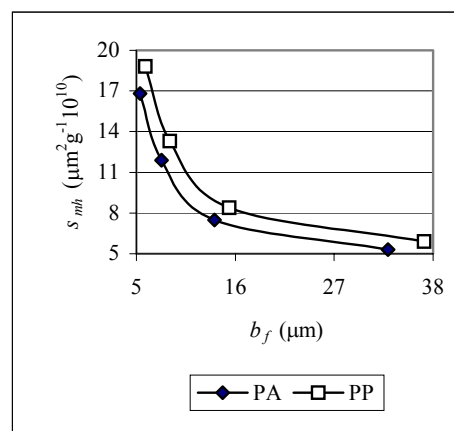


**Fig. 7.** Relations between index  $b_f$  and index  $s_{vh}$ . PA – polyamide fibre, PP – polypropylene fibre

$T_{fh}$ , we also have a fixed mass of hollow fibre. Thus, index  $s_{mh}$  has the same tendency of increase (see Fig. 4) as previously described indices  $d_{fo}$  and  $S_{fh}$ . Also, the index  $s_{mh}$  is higher for PP fibres compared with PA fibres (Fig. 4) as in the graphs for the indices  $d_{fo}$  and  $S_{fh}$  (Fig. 1 and 2).

Meanwhile Fig. 3 shows reverse tendency on this point: the index  $s_{vh}$  for PA fibre is above this index for PP fibre.

Another series of relations is computed for the variable of wall thickness  $b_f$ . These relations are shown for the indices  $d_{fo}$ ,  $S_{fh}$ ,  $s_{vh}$ , and  $s_{mh}$  in Fig. 5 – 8, respectively.



**Fig. 8.** Relations between index  $b_f$  and index  $s_{mh}$ . PA – polyamide fibre, PP – polypropylene fibre

Contrary to previous tendencies shown for the index  $d_{fi}$  in Fig. 1, 2, and 4, an increase of the index  $b_f$  causes a decrease of the indices  $d_{fo}$ ,  $S_{fh}$ , and  $s_{mh}$  (Fig. 5, 6, and 8).

The relations for the index  $s_{vh}$  (see Fig. 7) also have a reverse character compared with the previous relations shown in Fig. 3.

It is also necessary to point out that differences between the structural indices for PA and PP fibres in Fig. 5 – 8 are identical to previously noted for these fibres in Fig. 1 – 4, respectively. For instance, since of different fibre density, the values of the  $d_{fo}$ ,  $S_{fh}$ , and  $s_{mh}$  (Fig. 5, 6, and 8) for PP fibres are higher the same indices for PA fibres in any case of fibre wall thickness. Due to the same reason, the index  $s_{vh}$  (see Fig. 7) is higher for PA samples compared with PP fibres.

The results of the current paper are applicable for predicting various properties of the hollow fibres and other materials produced on a basis of these fibres.

## CONCLUSIONS

On the basis of made assumptions and proposed relations such generalisations for the effect of hollow fibre indices (inner diameter and wall thickness) up on conventional structural indices  $d_{fo}$ ,  $S_{fh}$ ,  $s_{vh}$ , and  $s_{mh}$  are done:

- the hollow fibres differ essentially from the solid fibres with respect to the indices  $d_{fo}$ ,  $S_{fh}$ ,  $s_{vh}$ , and  $s_{mh}$ ;
- the hollow fibres with greater inner diameter exhibited greater indices  $d_{fo}$ ,  $S_{fh}$ , and  $s_{mh}$ ;
- the greater hollow fibre wall thickness, the less are the indices  $d_{fo}$ ,  $S_{fh}$ , and  $s_{mh}$ ;
- the highest values of index  $s_{vh}$  are characteristic to hollow fibres with minimal inner diameter, also to products with maximal wall thickness;
- the indices  $d_{fo}$ ,  $S_{fh}$ , and  $s_{mh}$  for PP hollow fibres are higher the same indices for PA fibres, while an opposite tendency is valid for index  $s_{vh}$ .

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