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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) regarding the integration of micro-systems 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 μm 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 μm 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 μm. These products are used for the purpose of filtration. Diameter of the hollow core of fibres used in laser-apparatus is 700 μm (see information in Web site 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 μm; the wall thickness of these fibres is between 3 and 20 μm in [10]. The other range of inner diameter varies between 150 and 200 μm [10]. The wall thickness for these samples is 5 to 8 μm [10]. Similar data of inner diameter (200 μm) and wall thickness (25 μm) are presented in [12]. Thick polyethylene hollow fibre with inner diameter greater than 4000 μm is proposed in [11]. Thickness of a porous wall of this fibre is more than 100 μm [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., $T_{fh} = T_f =$ 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) 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: $\rho = 1140$ kg/m^3 for PA fibres, $\rho = 910$ 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

$$T_f = \frac{\pi d_f^2 \rho}{4}, \tag{1}$$

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

Because of the second assumption, we have:

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

or

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

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

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

where l is the fibre length.
In a similar manner the equations for the indices s_{vh} and s_{mh} we re also proposed:

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

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

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

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

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

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

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

If $d_{fi} = 2d_f$ then

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

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

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

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

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

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

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

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.

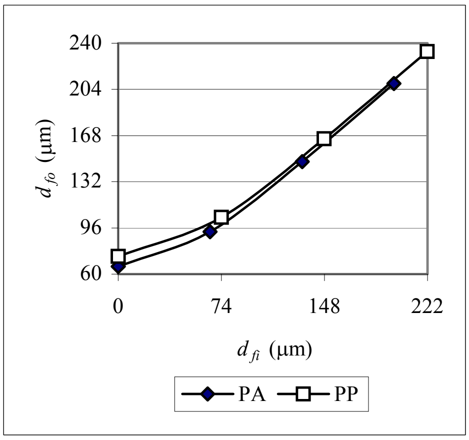

Fig. 1. Relations between index d_{fi} and index d_{fo}. PA– polyamide fibre, PP – polypropylene fibre

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

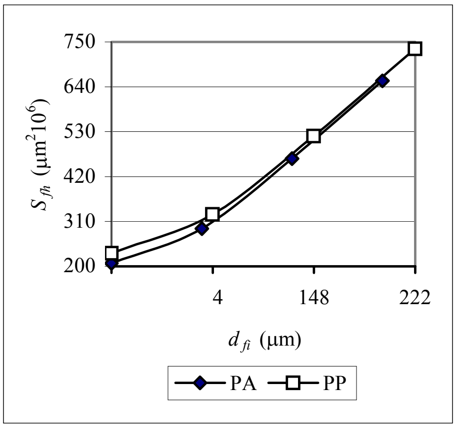

Fig. 2. Relations between index d_{fi} and index S_{fh}. PA– polyamide fibre, PP – polypropylene fibre

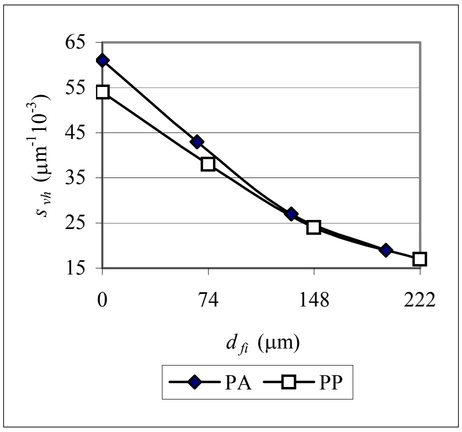

Fig. 3. Relations between index d_{fi} and index s_{vh}. PA – polyamide fibre, PP – polypropylene fibre

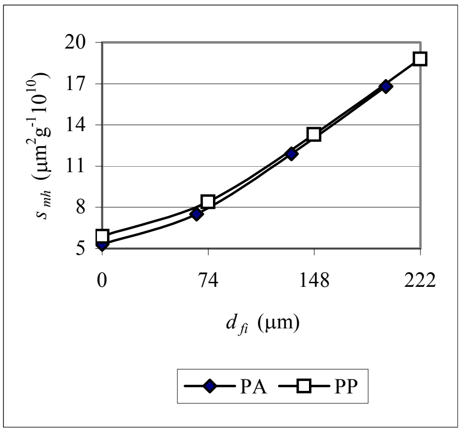

Fig. 4. Relations between index d_{fi} and index s_{mh}. PA – polyamide fibre, PP – polypropylene fibre

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

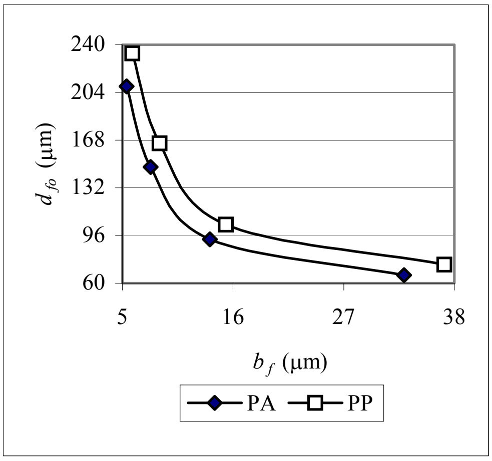

Fig. 5. Relations between index b_f and index d_{fo}. PA – polyamide fibre, PP – polypropylene fibre

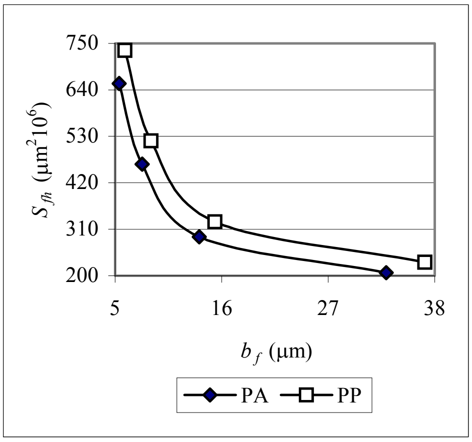

Fig. 6. Relations between index b_f and index S_{fh}. PA – polyamide fibre, PP – polypropylene fibre

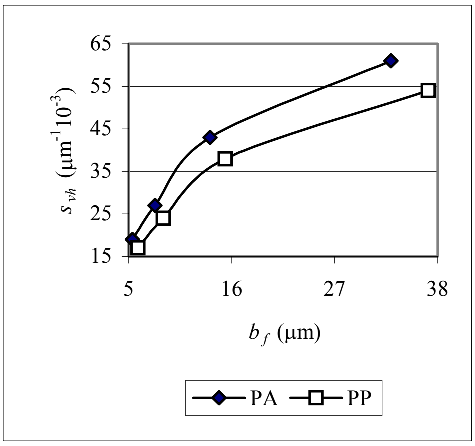

Fig. 7. Relations between index b_f and index s_{vh}. PA – polyamide fibre, PP – polypropylene fibre

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.

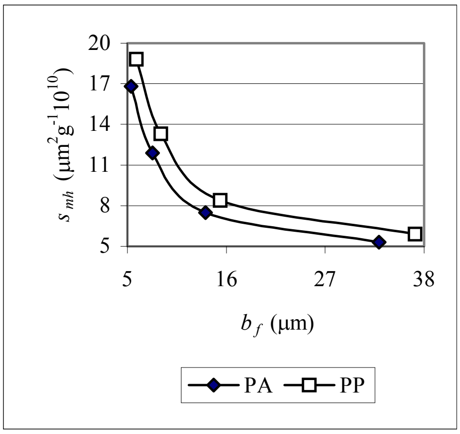

Fig. 8. Relations between index b_f and index s_{mh}. PA – polyamide fibre, PP – polypropylene fibre

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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