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Fractal character forecast of down fiber assembly microstructure

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Down fiber assemblies are used widely in thermal products in winter because of their excellent heat-insulating abilities. These consist of down fibers and air, and belong to a typical kind of porous material. The internal microstructures involved fiber arrangement and pore distribution affects assembly heat conduction greatly. In this article, the micro computer tomography as a nondestructive observing technique to assembly microstructure is introduced, and the mathematical method of “local fractal” is applied to forecast and characterize the fractal characteristics of the down fiber assembly microstructure. The parameter “local fractal dimension” quantifies the geometric complexity of both the fiber arrangement and the pore distribution in the assemblies.

Keywords: down fiber assembly; Micro-CT; microstructure; local fractal dimension

Introduction

Down fiber assemblies have excellent thermal insulation properties as filler materials in thermal products (Gao, Pan, & Yu, 2007b). The fiber arrangement and the pore distribution in down fiber assemblies are the crucial factors in thermodynamics engineering as they affect the thermal insulation strongly. Traditional approaches describe this kind of porous media as “average volume,” which suppose that the fiber arrangement and pore distribution are orderly, and only the parameter volume fraction is considered as the effect factor. However, these assumptions hardly agree with the practical situations, and the simplifications are inaccurate and inadequate in describing such porous media. From a practical point of view, it is desirable to have a universal means to quantify the relative fiber arrangement, which can be applicable to those analogous disordered systems. In response, this work introduces a method by which the fiber arrangement in the assembly cross-section is characterized as a local fractal object and described in terms of local fractal dimensions (Falconer, 1990; Pitchumani & Yao, 1991; Zhang, 1995).

Before presenting this mathematical method to quantify the assembly microstructure, effective microstructure-observing techniques are required right at the initial stages of research. An effective observing approach should be accurate and nondestructive and have high-resolution power while providing a comprehensive overview of the various morphological characteristics. Micro computer tomography (Micro-CT) (Saey & Dietmar, 2006) is a more recent method of examining the microstructure characteristics.

This work aims to employ this current approach to observe and evaluate the microstructure of down fiber assemblies, and then apply the local fractal theory to calculate the mathematical characters of local fractal dimension so as to further select or design down assemblies with the best warmth-retention properties.

This article is organized as follows. First, the Micro-CT method used to observe down fiber assemblies is introduced. Then the general definitions of fractal geometry and local fractal dimensions are given. The next section presents the local fractal dimension method used to characterize down fiber assembly. The results obtained are then presented and discussed. The last section presents the conclusions drawn.

Micro-CT method used to observe down fiber assemblies

Down fiber assemblies are composed of mass loose fibers. The internal structures can be destroyed easily by a general observing approach, such as slitting or embedding. By direct observation of the fibers in the container, the fiber layers will be confused. So considered, the single-layer fibers must be separated or taken out. The Micro-CT (Saey & Dietmar, 2006) is employed to observe cross-sections of down fiber assemblies. This technique requires high-resolution power and is nondestructive on the microstructure observation.

In this work, the SkyScan-1172 high-resolution desktop Micro-CT system, was used to observe the microstructures

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Figure 1. Down fiber assembly on container.

of down fiber assemblies. First, the down fibers of various volume fractions were filled into transparent column vessels made of polyester film, as shown in Figure 2. Then the vessel cross-sections were scanned by the Micro-CT system so that the disordered fiber arrangement and the pore distribution in the down assemblies could be observed clearly at nano levels.

Figure 3 shows the down fiber assembly observing screen at a certain volume fraction by Micro-CT. The top left corner on the screen displays various function bonds to control the viewing patterns and position. Especially, adjusting the bond “Position” changes the images of various positions along direction X , Y , or Z . Uniting the many images in various directions, they reflect the arrangement and action modes among fibers.

From Figure 3, it can also be seen that the distribution of fibers and pores in down fiber assemblies are evidently asymmetrical. The complicated micro space structures vary with the fiber diameter, length and arrangement. The fiber accumulate types and pore shapes are both random and ir-

Figure 2. Down fibers' sample in column vessel.

regular. Euclidean geometry describes the regular objects of macroscopical size using integer dimensions 0, 1, 2, and 3, respectively. However, it cannot describe the complexity of micro space structures of porous media like down fiber assemblies. The fractal geometry just happens to resolve such problems using fractal dimension. In order to quantify the complexity of fiber arrangement in down fiber assemblies, we employ the parameter of “local fractal dimension” described in the following section.

Fractal geometry and local fractal dimension

Fractal is a new subject developed only in recent years, which reveals the unifications between in-order and out-of-order and between determinability and randomness. The fractal structures have aroused a great deal of interest in different fields (Gabrys & Rybaczuk, 2005; Gao, Pan, & Yu, 2006, 2007a; Haba, Ablart, Camps, & Olive, 2005; He, 2004; Iovane & Varying, 2004; Stanley, 1985; Zmeskal, Buchniecek, & Vala, 2005).

First, there are great differences between conventional Euclidean geometry and fractal geometry (Falconer, 1990; Zhang, 1995). Euclidean geometry describes regular objects like points, curves, surface, and cubes using integer dimensions 0, 1, 2, and 3, respectively. However, most of the objects in nature, such as the surfaces of mountains, coastlines, microstructure of metals, etc. are not Euclidean objects. Such objects are called fractals and are described by a nonintegral dimension called the fractal dimension.

For example, if one were to measure the length of a coastline, the length would depend on the size of the measuring stick used. Decreasing the length of the measuring stick leads to a better resolution of the convolutions of the coastline, and as the length of the stick approaches zero, the coastline's length tends to infinity. This is the fractal nature of the coastline. Because a coastline is so convoluted, it tends to fill space, and its fractal dimension lies somewhere between that of a line (which has a value of 1) and a plane (which has a value of 2).

The measure of a fractal object $N(L)$ (namely, length, area, or volume) is governed by a scaling relationship of the form

$$N(L) \sim L^{d_f}, \quad (1)$$

in which the “ $\sim$ ” should be read as “scales as”, and d_f is the fractal dimension of the object. As an illustration of the above relationship, consider the microstructure of a metal showing grains of various shapes and sizes. This is a fractal object in a two-dimensional plane. It is observed that the average area $N(L)$ of the grains within the squares of different sizes L by L (defined as the arithmetic mean of only those samples for which the center of the square falls on the grain) scales with the length L over a range of lengths, as per the above relationship. The fractal dimension d_f

Figure 3. Observing screen of Micro-CT.

calculated as the slope of a log-log plot of $N(L)$ against L lies in the range $1 < d_f < 2$. Alternatively, the microstructure can be described in terms of two linear fractal dimensions, each having a value between 0 and 1, along mutually perpendicular directions. The linear fractal dimensions are obtained from a scaling relationship as in Equation (1), where $N(L)$ denotes the average total length of the intercepts between a measuring line of size L and the microstructure.

Associated with Equation (1) is the property of self-similarity, which implies that the d_f calculated from the relationship in Equation (1) remains constant over a range of length scales L . Exact fractals like the Sierpinsky gasket, Koch curve, etc., exhibit self-similarity over an infinite range of length scales. In actual applications, self-similarity in a global sense is seldom observed, and the “fractal” description is usually based on a statistical self-similarity, which the objects exhibit in some average sense, over a certain local range of the length scale L , which is of relevance to the problem. The fractal dimension calculated on the basis of the local statistical self-similarity is termed the local fractal dimension to distinguish from the term fractal dimension, which implies global self-similarity at all length scales. The fractal dimensions (local or global) of statistical fractals are usually estimated in the same man-

ner as in the illustration of the microstructure, using a scaling relationship between $N(L)$ and L of the form in Equation (1).

Local fractal procedure used to characterize down fiber assembly

A down fiber assembly cross-section, although it may not be an exact fractal by nature, exhibits statistical self-similarity over a small range of length scales around a fiber. It is observed that the average fiber area $N(L)$ enclosed within the squares of different sizes L by L scales with L in accordance with Equation (1) over a range of length scales spanning a few fiber diameters. Because of the small range of length scales, the use of the term “local fractal” seems appropriate, although the present range is much smaller than those in conventional fractal applications.

The following procedure for evaluation is a variation of the “Sandbox method” of measuring local fractal dimension (Figure 4), proposed by Stanley (1985):

- (1) Discretize the fiber assembly cross-section into a number of grid cells so as to ensure equiprobable samplings in the procedure described below. Typically, grid cells about one-tenth the fiber diameter in size provide a good resolution of the cross-section.

Figure 4. Sketch map of the "Sandbox" method.

- (2) By placing a line of length L parallel to the direction of heat flow on every grid cell, systematically scan the entire cross-section. This is equivalent to a purely random sampling with every cell being an equally probable origin for the measurement. Each time the center of the line falls on a fibrous region, record the total length of the intercepts between the line and the fibers. The

average of these intercepted total lengths is the mean length $N(L)$.

- (3) Considering that the heat transfer of fibers is related only to the neighboring fibers, choose $d \leq L \leq d + 1$ as the measure range. Repeat step (2) for several values of L within the measure range, and make a log-log plot of $N(L)$ against L .
- (4) The slope of the best line fit through the points in this plot gives the exponent in Equation (1), which is the local fractal dimension d_f .

Results and discussion

Figure 5 shows the cross-section images of down fiber assemblies with $V_f = 0.001162$, 0.001960 and 0.005659, respectively, wherein the white parts represent the down fibers and the black parts represent the pores. As it can be seen, as the assembly volume fraction increases, the fibers are packed more closely, and the distribution of both fibers and pores is more complicated.

(a) $V_f = 0.001162$

(b) $V_f = 0.001960$

(c) $V_f = 0.005659$

Figure 5. Cross-section images of down assemblies with various V_f .

Figure 6. Log-log plots of $N(L)$ against L .

Selecting the box side $2 \mu\text{m}$ and $30 \mu\text{m} < L < 100 \mu\text{m}$, the “Sandbox” method is employed to create the images, respectively. The log-log plots of $N(L)$ against L can be obtained, as shown in Figure 6. The figures reflect excellent line fits in all three situations. Linearity relativities reach 0.99. The linearity equations, respectively, are as follows:

$$\begin{aligned} \ln(N(L)) &= -5.91 + 1.589 \ln(L), \\ \ln(N(L)) &= -5.59 + 1.601 \ln(L), \\ \ln(N(L)) &= -5.98 + 1.653 \ln(L). \end{aligned} \quad (2)$$

So the local fractal dimensions can be calculated as 1.589, 1.601 and 1.653, which explain an obvious fractal ability of fiber arrangement in the cross-section of down fiber assemblies.

From the results, we conclude that a closely packed array, corresponding to a high degree of “connectedness” or “contact” among fibers, and the distributions of both fibers and pores are more complicated. Consequently, the relevant local fractal dimensions will increase and be closer to 2, which means that the fibers tend to fill with the plane on the assembly cross-section as the fractal dimensions increase. Conversely, the farther away the fibers are relative

to one another, the smaller is the value of the local fractal dimension.

Conclusions

As a typical kind of porous material, a down fiber assembly is filled with mass loose fibers. Its microstructure can be destroyed or confused easily by a general observing method. In this article, the Micro-CT method is employed to observe and assess the microstructure of the down fiber assembly nondestructively, and the clear images of assembly cross sections can be gained by high-resolution power. The results show that in the fiber assemblies, the fiber arrangement and the pore distribution are not symmetrical as was presupposed. Fiber accumulate types and pore shapes vary momentarily with fiber diameter, fiber length, and various positions. As the assembly volume fraction increases, the fibers are packed more closely.

The "Sandbox" method in fractal geometry is used to forecast the fractal characters and calculate the local fractal dimensions of the gained cross sections in this work. The results indicate that the log-log plots of $N(L)$ against L assess excellent line fits, and the linearity relativities reach 0.99, which would explain the obvious statistical self-similarity and local fractal characters of fiber arrangement in cross sections of down fiber assemblies. As the assembly volume fractions increase, the values of the local fractal dimensions will be closer to 2.

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