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Large Scale Capillary Based Plastic Heat Exchangers

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The first measurements of the capillary based heat exchangers are just several years old. Moreover the used pilot heat exchangers had just negligible heat transfer area generated by 10 fibres with diameter of 0.3 mm and length of 100 mm. It was therefore a relatively easy task to make sure that the relevant heat transfer can achieve the optimal conditions. However, industrial applications require large heat exchangers to make their operation feasible. If a capillary heat exchanger has 1000 - 30,000 fibres, each fibre is 600 (or 3000) mm long then it is a very difficult task to achieve the optimal conditions of heat transfer e.g. by making sure that each fibre takes an optimal part in the heat transfer. An important additional requirement is that the cost of the plastic heat exchanger must be low, preferably very low, if compared to other types of heat exchangers. There is no substantial industrial know-how. Therefore common sense reasoning is the main source of ideas. To demonstrate problems related to e.g. potting the following photographs are given to demonstrate the middle part and one end of the 30,000 fibres ponytail.

1. Introduction

Heat exchanger design is a complex task. Many factors have to be considered e.g.: heat transfer rates, fouling, power consumption, flow induced noise and vibration, etc. and quite often a compromise must be made, see e.g. Bouris et al. (2005).

Figure 1: Potting cut – ovality test

Solid materials holding promise for use in heat exchangers can generally be divided into four categories polymers, metals, ceramics and carbonaceous materials (Sommers et al., 2010). However,

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there are many reasons why several heat exchangers applications do not perform satisfactorily in their unmodified form. Flexibility of used heat exchangers is an important aspect as far as defouling is concerned. Such materials, which are not sufficiently flexible, cannot be therefore used, see e.g. Cho et al. (2004).
Flexibility of used tubes depends heavily on their geometric dimensions, namely inside / outside diameters and their length. An example of dimensions is the length of 0.9 - 1.2 m, outside diameter of 5 - 7 mm and a the wall thickness of 1 mm. Such pipes are not sufficiently flexible and defouling processes based on whipping are not applicable (T'Joen et al., 2009).
Some parameters are very difficult to control, e.g. fibre ovality after potting. One must keep in mind that any control of one kilometre long capillary must be very cheap, just several cents is an acceptable cost. Potential ovality deformation can be studied by potting analysis. Frequencies of failures of all sorts are usually caused by low quality of potting and not by fibres themselves. Therefore a camera record of a potting cut is done (see Figure 1).

2. Flexible heat exchanger development

Flexible heat exchangers use fibres which are kink resistant. Therefore it is possible to bend them with no loss of integrity. Table 1 gives typical parameters of a large scale flexible heat exchanger.

Table 1: An example of a PSC (Potted set of capillaries)

Property	Value of property
Capillary material	Polypropylene
Plotting material	Polyurethane
Number of capillaries	1500
Total length	600 mm
Capillary inner diameter	0.525 mm
Capillary outer diameter	0.595 mm
Burst pressure	4 bar
Collapse pressure	2 bar
Max operating temperature	70 ˚C
Approximate heat transfer area	0.9 m^2

Figure 2: Very large ponytails with 30,000 capillaries on the left, ponytails with 30,000 fibres 3,000 mm long on the right

It is not difficult to identify the most important problem of large scale capillary heat exchangers. Each fibre must be active, i.e. each fibre must transfer heat. Previous results indicated that if a number of

capillaries as below certain upper limit e.g. 1000 - 2000 then a trivial idea of overlength is sufficiently effective.
When the distance D between both pottings (ends) is fixed and L is the total length of the fibres, then the overlength O is defined as follows

$$O = 100(L - D)/L. \tag{1}$$

The flow keeps the fibres moving if the fibres are sufficiently free to move. Therefore simple straight fibres can be used.
However, partially straight fibres could be a better heat transfer variant, see Figure 3 on the right.
Unfortunately, it is prohibitively difficult to produce partially straight with no sharp kinks. The kinks can decrease the heat exchanger life time etc.
There are two extremes – totally straight hollow fibres, see Figure 3 on the left, and curly-haired fibres, see Figure 4 on the left. Operation of flexible heat exchangers is heavily affected by the shapes of fibres. The shape of fibres must be therefore quantified.
It is obvious that the level of curliness is an important parameter which affects two aspects, namely the heat transfer and the manufacturing cost. The papers study such fractal evaluation as an algorithm how to quantify the hollow fibre curliness. It describes certain relations between general and specific knowledge items (for example between on-line measurements and general rules of thumbs). A simple idea of an information volume is adopted to screen knowledge bases. The chaos analysis is used to quantify one aspect of knowledge base „quality“, namely general and specific consistencies.
The fractal analysis gives a numerical parameter (fractal dimension). There are many published papers which deal with different aspects of the fractal evaluations on mathematical level or specifically their applications in chemical engineering.
A fuzzy fractal interpretation given in appendix is based on mutual relations between general knowledge items and details. The ability to distinguish between a detail and a general knowledge item is the only prerequisite for the following fractal analysis.

Figure 3: Straight fibres on the left, partially straight fibres on the right

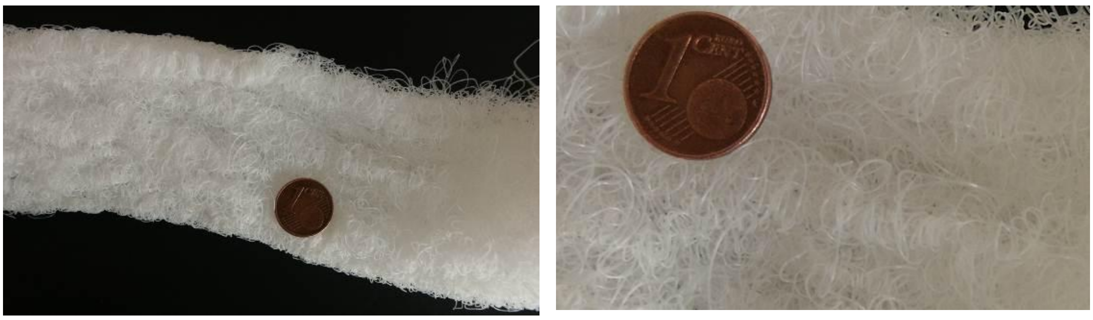

Figure 4: Curly haired fibres on the left, photograph used to evaluate the fuzzy fractals on the right

The input information item into the fuzzy fractal analysis is a photograph(s). The photograph given in Figure 4 on the left is not optimal. It makes no sense to study a single fibre. However, there is an important relation among:

- Hollow fibre diameter
- Number of fibres
- Fibres shapes / curliness.

Unfortunately it is not clear what the optimal scale of photographs is. The Figure 4 on the right is much better for the fuzzy fractal analysis.

3. Conclusion

Heat exchangers have been studied for a very long time because of their importance. There is a relatively long history of plastic heat exchangers as well. Their advantages are relatively well known. However, there are many unsolved problems. A short list of some examples follows:

- Life time
    - Potting
    - Fibre
- Surface cleaning

It will take some time to optimize all aspects of flexible plastic heat exchangers.
Compact heat exchangers are in the very centre of heat exchanger manufacturer's attention due to their enhanced thermal performance and energy saving benefits. Polymers have some advantages and some disadvantages if used for construction of heat exchangers. Advantages are cheap raw material, easy to shape, e.g. extrusion and form, low specific densities and consequently low mass of heat exchangers, smooth surface, i.e. low friction i.e. low pressure drop, high chemical and corrosion resistance, large surface area/volume ratio. Disadvantages are low thermal conductivity, which is order of magnitude lower than metal conductivity, know how shortage, high thermal expansion (potting problems).

4. Appendix 1: Fuzzy fractal interpretation

Suppose a black and white TV camera is used to observe a two dimensional object. This object is recorded from several different camera-object distances. The camera sensitivity is constant, so, as the camera-object distance increases, only more and more significant features are distinguishable. As a result of these records the following set of pairs is obtained

$(T_i, S_j); i = 1,2,...,n$, T_i … the i-th camera-object distance, S_i … the i-th TV image. (2)

Each screen record S_i contains a set of black and a set of white pixels:

$S_i = (B_i, W_i); i = 1,2,...,n$, *$B_i$ (W_i)*… the set of black (white) pixels on the i-th image. (3)

An isolated black pixel i.e. a detail disappears if the distance T (Eq. 2) increases. A substantial feature represented by several pixels can be recorded even from a large distance.
A simple common sense analysis shows that:

if $T_i < T_{i+1}$ then $L_i < L_{i+1}$,
$L_i = Car(B_i)/p$,
$p = Car(B_i + W_i)$, *Car(F)*… the Cardinality of the set F. (4)

The total number of black pixels will gradually decrease as the camera-object distance increases. However, the total number (black plus white) of screen pixels is constant and equal to p (see Eq. 4).

The function

$$L = f(T) \tag{5}$$

is obviously non-increasing. The following specification of function in Eq. 5

$$L(T) = K \cdot T(1 - D), \quad K \text{ is positive constant} \tag{6}$$

was based on empirical observations.
From Eq. 6 it can be seen that according to fractal analysis two parameters are needed to characterize the function (Eq. 6), namely K and D. The parameter D is a measure of the degree of 'roughness' of the object being measured. This parameter corresponds to the fractal dimension.
The fractal dimension can be easily evaluated provided the relation L - T (Eq. 6) is known quantitatively:

$$\log(L) = \log(K) + (1 - D) \times \log(T). \tag{7}$$

5. Appendix 2: Primitive fuzzy interpretations

The basic ideas of fractal knowledge analysis are generally applicable regardless of type of knowledge bases. Practically any calculus (e.g. statistics, fuzzy/rough sets, qualitative reasoning) can be used to quantify fractal dimension and characterize the type of question.
Let us suppose that the following set of fuzzy conditional statements, a fuzzy knowledge base F is a result of a sequence of knowledge acquisition activities:

$$\begin{array}{lllll} \text{if} & r_1 & \text{then} & B_1 & \text{or} \\ \text{if} & r_{2,1} & \text{then} & B_2 & \text{or} \\ . & . & . & . & . \\ . & . & . & . & . \\ \text{if} & r_m & \text{then} & B_m & \end{array}, \text{ where } r_i = A_{i,1} \text{ and...... and } A_{i,n}. \tag{8}$$

Fuzzy sets

$$A_{i,j}, B_i; i = 1,2,..., m; j = 1,2,..., n, \tag{9}$$

are one-dimensional fuzzy sets (a piece wise linear grade of membership, see Figure 5) and can be easily specified or/and modified using points a, b, c, d.
A similarity s of two n-dimensional fuzzy sets r_i, r_j is

$$s(n, r_i, r_j) = s_{i,j}. \tag{10}$$

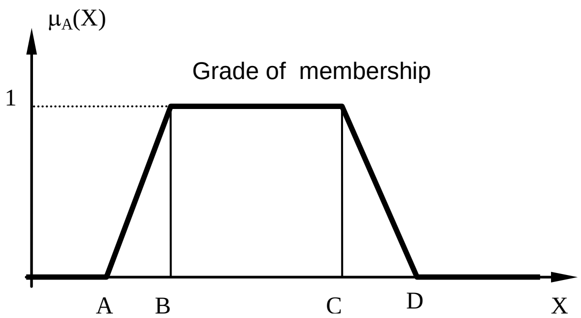

Figure 5: Piecewise linear description of the grade of membership function

The ratio L, as defined in Eq. 7, is a measure which corresponds to a one-dimensional object (line). A fractal analysis of an (n + l) -dimensional fuzzy model (see r_i Eq. 8) needs a (n + 1) -dimensional volume V:

$$z_i = r_i \text{ and } B_i . \tag{11}$$

The n-dimensional fuzzy set z_i (Eq. 11) and n + 1 dimensional volumes are as

$$V(r_i) = \prod_{j=1}^{n} \left(d\left(A_{i,j}\right) - a\left(A_{i,j}\right) \right) \times \left(d(B_i) - a(B_i) \right), \tag{12}$$

where $d(A_{i,j})$ is point d (see Figure 5) of the grade of membership function of the one-dimensional fuzzy set $A_{i,j}$. The same notation is used for points b, c, d (see Figure 5).
Roughly speaking only "volumes" of fuzzy statements in Eq. 12 are considered and not their layout. The following simple algorithm is used for detail elimination:

if $V(r_i) < U$ then $aV(r_i) = 0$ else $aV(r_i) = V(r_i)$, i=1,2, . . ., m, (13)

where U is a threshold volume which is used as a sort of n-dimensional measuring unit and aV(ri) is a screened volume. The total volume of the fuzzy model Eq. 8 can be evaluated using following expressions:

$$Yv = \sum_{i=1}^{m} V(r_i), \quad YvU = \sum_{i=1}^{m} aV(r_i) \tag{14}$$

The total volume YvU is a function of U in a strict analogy with the chaos interpretation given above (see Eq. 9). T corresponds to U and L is corresponds to Yv. The functions in Eq. 14 enable the evaluation of the fractal dimension D. The slope of the straight line (see Eq. 11) is equal to

$$(1 - D) \tag{15}$$

The fractal dimension D (Eq. 15) is an oversimplification. Rather often two distinctive behaviors can be identified. This fact is reflected by two straight lines (piece wise linear) that might be obtained as the final result of a fractal analysis. The fractal dimension Dd characterize the details and Dg reflects the existence and significance of more general trends.

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