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Fuzzy Fouling Model of Large Scale Flexible Plastic Heat Exchangers

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Flexible plastic heat exchangers (FPHE) are heat exchangers based on flexible plastic capillaries. The diameters of the capillaries are 0.3 – 1.0 mm. Medical applications of FPHE are the only area where such heat exchangers have a long tradition and therefore extensive experience, blood cooling. However, such experience has practically no relevance for chemical engineering. Moreover the blood cooling is nearly always integrated with the blood oxidation which makes the FPHE application even more specific. Chemical engineering applications, e.g. crystallization, low cost low temperature cooling, are therefore not well known.
Fouling itself is multidimensional, interdisciplinary, vague, inconsistent, partially subjective and sparse. Therefore sever information shortage exists and even very uncertain knowledge is valuable. This is the reason why highly subjective information items as e.g. experience must be taken into consideration and models must be based on them.
A team of experts is probably the most important source of fouling knowledge. Biofouling was chosen as an important sub problem. Artificial intelligence has developed several formal tools to deal with different networks of such knowledge items. A multidimensional fuzzy model of FPHE fouling is described in details. There are nearly 300 simple fuzzy conditional statements.

1. Introduction

Fouling affects nearly every plant relying on heat exchangers and introduces costs which are ultimately related to the conservation of energy, operation, and capital investment. There are two strategies how to deal with such problems (Georgiadis et al., 2000; Cheng et al., 2009):

- Defouling, i.e. removal of existing fouling,
- Antifouling, i.e. design and operation of heat exchangers to minimize all (some sorts of) fouling.

Simple common sense reasoning indicates that specific methods of defouling and antifouling depend on specific types of heat exchangers and their mode of operation, see e.g. Zaheed et al. (2004).
Plastic heat exchangers are in the centre of attention of heat exchanger manufacturers. However plastic capillaries are used as the basic elements of heat exchangers relatively recently, for details see Zarkadas et al. (2004). Polymers have well known pros and cons e.g. smooth surface (i.e. low friction, low pressure drop), high chemical and corrosion resistance, large surface area/volume ratio or low thermal conductivity, which is an order of magnitude lower than the metal thermal conductivity. Their high thermal expansion causes the potting problems, but it is much cheaper and easier to shape, form

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and machine them in comparison to metals. Also their densities are several times lower resulting in much lower construction and installation costs (Zarkadas et al., 2004).
The obvious way how to minimize the negative consequences of the low thermal conductivity is to use thin wall of hollow fibres. There are two aspects which must be taken into consideration if the wall thickness is minimized, namely a strong correlation of the outside and inside fibre diameters and mechanical robustness of the hollow fibre.
A PSC (Potted Set of Capillaries) made from flexible raw material, e.g. polypropylene or PVDF, can be used as the key heat exchanger element to produce low cost, flexible, corrosion resistant heat exchanger systems analogous to well-known tube and shell type of heat exchangers.

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

Property	Value of property
Capillary material	Polypropylene
Plotting material	Polyurethane
Number of capillaries	30 000
Total length	3000 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	4 m^2

2. Whipping

The flow-induced vibration in heat exchangers is a detrimental factor for causing the heat exchanger damage. An effective hydro-dynamic vibration device for cleaning inner surfaces of heat exchanger pipes is another example of the obvious fact that mechanical movement can be used to minimize fouling (Grinis, 2005). However, heat exchanger pipes are not flexible enough to take advantage of some movements of the capillaries themselves and not just movement of liquids.
The PSC are used in two different modes, namely submerged and in housing. An example of a set of submerged PSC is in Figure 1.
A series of air bubbles keep all fibres of PSC in a movement. If the source of air has pressure over 3 bars then the PSC are literally whipped and efficiently mechanically cleaned. Defouling and / or antifouling done by whipping have been extensively tested for membrane bioreactors. The operating conditions for PSC and submerged bundles of hollow fibre membranes are very similar if not identical. The key difference is the filtration cake.

Figure 1: Set of submerged PSC

Figure 2: Left figure shows a large ponytail of fibres, right figure shows large PSCs

3. Large PSC

There is a natural tendency to increase the number of fibers in one PSC to increase the total heat transfer area. However, this increase has natural limits. One of the limits is a possibility to de-foul them efficiently. Simple common sense reasoning indicates that to keep clear fibers inside a large ponytail, see Figure 2 on the left, is difficult. Moreover e.g. potting of large PSCs is a tricky task as the surface of precursors used for PSC manufacturing is very smooth not mentioning the fact that to reach the total integrity of the potting is not easy, see Figure 2 on the right.

4. Large PSC fuzzy models

At present, most of the techniques employed for the analysis of complex problems possess analytical or statistical natures. Unfortunately these precise mathematical tools do not always contribute as much as is expected towards a full understanding of complex task. We cannot expect to be able to analyze completely rigorously a complex real problem using conventional techniques (analytical or statistical).

A simple and efficient way to minimize the loss of valuable knowledge represented by a set of heterogeneous clusters of measurements is fuzzy reasoning. Fuzzy reasoning can be used as an interpolation. A fuzzy set represents an optimal trade-off between the absolutely precise number and a vague verbal quantification (Hurme et. al., 1993).

Fuzzy set theory is based on the premise that the key elements in human thinking are not numbers but words. The most important feature of human thinking is the not yet well-understood ability to extract from a collection of masses of data only such items of knowledge which are relevant to the task at hand (Zimmermann, 1986, Filev et. al., 1991).

Defouling of large PSC is a complex, multidimensional, difficult to measure task of interdisciplinary nature. This is nothing exceptional in chemical engineering. Fuzzy models have been used to solve such problems routinely and it is not explained why.

A complex dialog

Experts → Fuzzy Knowledge base of an expert system → Experts (1)

required many evaluations of fuzzy model inconsistency and similar parameters.

The following model solves just one sub problem namely biofouling of large PSC. Biofouling knowledge is multidimensional, vague, inconsistent, partially subjective and sparse. A suitable data and knowledge integrator is a set of fuzzy conditional statements which can be flexibly expanded and/or modified. However biofouling community is not willing to accept a black box approach towards applications of artificial intelligence algorithms. A transparent and easy to understand fuzzy reasoning

is therefore used. No single model or a knowledge base of an expert system can integrate all biofouling knowledge items of different origins, e.g. tables, graphs, equations, observations etc. into a manageable information network.
The following variables were chosen by a team of experts:

Table 2: The variables chosen by a team of experts

Variable	Dimension	Abbreviation
Temperature interval	˚C	TI
Charge density of capillary surface/zeta-potential	mV	ZP
Plant design, relative dead zone volume	% of feed path	PD
Redox potential	mV	RP
Technological mode	-	TM
Pretreatment scheme	-	PS
Feed type	-	FT
Tendency towards biofouling	%	BIO

The fuzzy knowledge base is used to quantify the following ill-known, multidimensional relation:

$$BOI = f(TI, ZP, PD, RP, TM, PS, FT) \qquad (2)$$

Fuzzy description of the relation (2) is a very similar task to many chemical and bioengineering tasks and therefore is not studied in this paper.

5. Fuzzy interpolation

Let us take as an example of a verbal variable BUF. To quantify expert knowledge, a set of verbal values, i.e. a dictionary, is needed. Such the BUF “verbal dictionary” could be the following set: very low, low, medium, high, and very high. The linguistic value is transformed into the fuzzy set by the specification of a grade of membership. For example, the verbal value low BUF is transformed into a fuzzy set by the grade of membership function given in the left graph in the Figure 3.
An unknown n-dimensional relationship

$$Y = \phi(X_1, X_2, ..., X_n) \qquad (3)$$

is studied.
The only available information is a matrix

$$M[m, (n+1)], \qquad (4)$$

where m is the total number of different investments. The last column gives the values of the dependent variable Y.

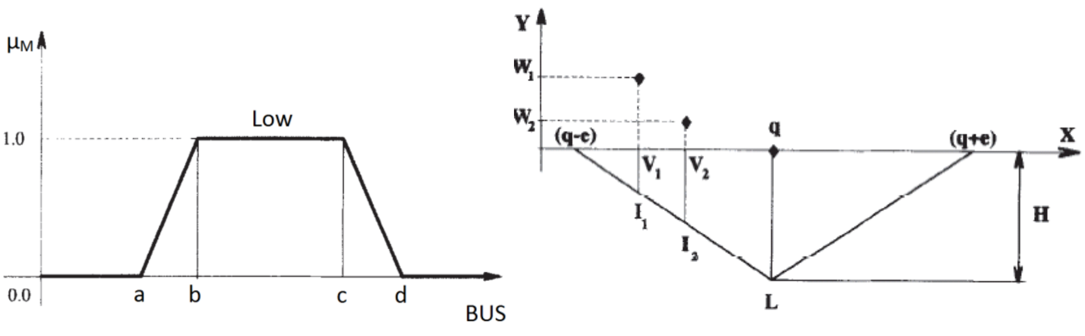

Figure 3: The left graph is piecewise linear description of the grade of membership function; the right graph is an optical analogy of fuzzy defocusing

The relation (3) is approximated by a function

$$Y = \Phi(X_1, X_2, ..., X_n), \tag{5}$$

that is used to "substitute" the unknown function Φ (3).

To use the observation results (5) directly, an interpolation or correlating algorithm is needed. To cover obvious requirements which can be easily deduced from the typical features of the results of measurements / observations, a suitable interpolation algorithm must be capable of interpolating data which are multidimensional, non-equidistantly spaced, variously accurate (vague), spares. Data have different weights for variables and measurements / observations assigned by different users.

The theory of interpolation does not offer an algorithm which is robust enough to cover all practical situations. The fuzzy reasoning algorithm is therefore used to "interpolate" or "correlate". The interpolation itself is done by a fuzzy reasoning mechanism of which there are many.

The complex mathematical details of fuzzy reasoning are not too relevant for the end user / non mathematicians. Let us rely on a simple geometrical interpretation of two-dimensional interpolation algorithm.

However, because of the very nature of the best fit algorithm, all experimental / observation outcomes are taken into account in "positioning" the curve C. Any query, however, is "local". Is it a good idea to let the answer be affected by all experimental result? Would it be better if the closest measurements to the query were considered as more relevant?

A graphic representation of a one-dimensional interpolation (n = 1, see Eq. 3) is presented in the right graph in the Figure 3. There are m numerical values V of the independent variable X and the corresponding numerical values W of the dependent variable Y (5):

$$X \equiv \{V_1, V_2, ..., V_m\} \tag{6}$$

$$Y \equiv \{W_1, W_2, ..., W_m\}$$

The one-dimension query Q is represented by its numerical value q. There is no numerical value of the independent variable X in expression (6) that is equal to the value q.

Imagine now that a source of light L is placed at a distance H below the numerical value q in the right graph in the Figure 3. The light beam is totally focused and is represented by an infinitely narrow interval Lq. The whole X-axis is dark, the only exception being the point q. A one-dimensional defocusing algorithm smoothly transfers the light interval Lq into a light triangle

$$(q - e), L, (q + e) \tag{7}$$

Let us suppose that the triangle covers only the following two values on the X-axis which are of interest (corresponding to the X-coordinates of points W_1 and W_2)

$$V_1, V_2 \tag{8}$$

and that the light intensity at these points is represented by the length of the lines

$$V_1I_1, V_2I_2 \tag{9}$$

The light intensity is "proportional" to fuzzy similarity s of the query q and two numerical values V_1, V_2. The following weighted average is thus used to "interpolate" the value of the dependent variable which corresponds to query q

$$\frac{W_1 \cdot V_1I_1 + W_2 \cdot V_2I_2}{V_1I_1 + V_2I_2} \tag{10}$$

A general formula for one-dimensional interpolation is a fairly straightforward extenuation of the expression in Eq. 10. The key problem is the choice of the height H and the defocusing algorithm that is the algorithm that controls the defocusing e.

There are several geometrical interpretations of fuzzy reasoning as an interpolation algorithm. The one presented above reflects all substantial features of the fuzzy reasoning as an interpolation algorithm. The one presented above reflects all substantial features of the fuzzy reasoning algorithms used below. However, equally efficient interpolation can be based on the simple idea of moving the light source L (see the right graph in the Figure 3) away from the point q without any additional defocusing.

6. Conclusion

Plastic heat exchanger will be naturally used just within such limits which are easily predicted by the parameters of the relevant polymers and the potting materials. However such area as bioenergy and related areas can profit significantly. Unfortunately there is not known – how obtained on large scale industrial base. This is the reason why such vague formal tool as fuzzy sets must be used.

Biofouling knowledge is multidimensional, vague, inconsistent, partially subjective and sparse. A suitable data and knowledge integrator is a set of fuzzy conditional statements which can be flexibly expanded and/or modified. However biofouling community is not willing to accept a black box approach towards applications of artificial intelligence algorithms.

Biofouling science represents a heterogeneous complex of various types of information. Practical biofouling problems are complex, integrated, ill known, usually difficult and expensive to measure. They may be subject to complex relations with their surroundings, which may make it nearly impossible to isolate them without a substantial distortion of the available knowledge.

The fuzzy model presented in the paper is an attempt to develop a model, which can be used to solve industrial problems. However, further study is required namely confrontation of the model and industrial observations. However, such confrontation requires cooperation with those who did not participate in development of the model. A specific measurement is, from the point of view of fuzzy logic, a fuzzy statement. A set of experiments can be therefore easily incorporated into the set of statements. The consistency test can be used to evaluate if the measurements reject or confirm some statements generated by the experts.

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