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Dealing with uncertainties in engineering problems using only available data

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ABSTRACT

This paper is the second in the series of three addressing the problem of how to deal with uncertainties in the modelings of engineering problems using only available data. The problem of the heat exchanger was selected as the example because it is sufficiently complex but still simple so that the difficulties and ideas will be apparent. There are various theories on how to treat the uncertainties in the first paper. In the series we use only the fuzzy set, respectively the possibility theory. In this paper we use the fuzzy approach for some model parameters and the probability approach for the others. The third paper will use the Bayesian theory.

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1. Introduction

During last few years the problem of modeling with uncertainties, the Calibration, Validation and Quantification of Uncertainties (C&V&UQ) came into the forefront of interest. Let us mention for example [1,2], NAS [3] and literature there. The formulation and numerical treatment of mathematical models for use in support of engineering decision making in the fields of solid mechanics is addressed in a document issued by the American Society of Mechanical Engineers (ASME) and adopted by the American National Standard Institute (ANSI) [4]. There are many papers addressing various aspects of uncertainties in the modeling problems. For example, we mention [5–8] and also two special journals addressing these questions were created recently.

The problem of the quantification of uncertainties is not easy. During the last 40 years various approaches were proposed. The basic ones are the following:

1. The worst scenario approach, see e.g., [9,10].
2. Interval analysis [11–13].
3. Fuzzy theory. There is large literature on the Fuzzy theory and a special journal, see e.g., [14–24] and citation there.
4. Dempster–Schafer evidence theory [25–27,15].
5. Possibility theory, see e.g., [15,28,16].
6. Rough set theory, see e.g., [15,29,30].
7. Probability theory, Bayesian probability [31–37].
8. The combined theories as fuzzy probability [21], fuzzy Bayesian Inference [38,39], etc.

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These theories are addressing uncertainties. All can be used in the modeling engineering problems and their uncertainties. The Major question is which of these theories should be used in the particular problem. Obviously the selection has to depend on the available information and data, their uncertainties and the knowledge and the experience of the analyst. Application of the above mentioned theories needs a specific characterization of the uncertainties. For example, the fuzzy set and the possibility theory need the membership functions, the evidence theory needs the focal elements, the probability theory needs the probability functions and the priors, etc. These characterizations are based on the available data and information which always have larger or smaller uncertainties. The basic sources of these uncertainties are:

1. Lack of the data resp. information.
2. Conflicting data resp. information.
3. Abundance and complexity of information resp. data.
4. Ambiguity of the information.
5. Not sufficient information for example, about the measurements.

As we said above, there is large amount of literature about uncertainty theories, modeling, calibration and validation. Unfortunately most of the papers and books bring only simple illustrative examples with synthetic data and are not addressing problems of reasonable complexity and the available data. This leads to the motto of the Helsinki 2012 conference [40] – "OK. These approaches are interesting, but does all of this actually make any practical difference in the real-world decisions?". Ultimately the analyst has to present the quantity of interest, its uncertainty and his confidence in his results. It depends on available data, etc. Finally, he has to present his results and the confidence in an understandable way to the decision maker.

This paper is the second in the series of papers addressing an engineering problem which has a reasonable complexity and is using only data which are available in the literature. The goal of the paper is to show the difficulties dealing with the information which have all five reasons mentioned above. The problem we have chosen is the problem of fouling in an heat exchanger. In the first paper [41] we have used the fuzzy description of all the parameters of the available data considering the fouling formation given. In this paper we are considering a fouling model and using different uncertainty characterization for different parameters as a function of the available data. In the next paper (in preparation) we will use the Bayesian probability approach.

The heat exchangers are typically overdesigned by 70–80% being 30–50% of which is attributed to the fouling. The overdesign is directly related to various uncertainties in the data and the prediction. According to the literature estimates for overall cost of fouling related issues in 1993 were about 15–20 US$ billions. This paper describes differently the uncertainties in the particular parameters of the heat exchanger model. We use the fuzzy set resp. the possibility and necessity approach to some, and the probability to others. We also show how to present the uncertainty in the quantity of interest when the various theories are used.

2. The heat exchanger problem

We consider the simplest heat exchanger consisting of a single AISI-304 stainless pipe for cooling hot water, located in the neighborhood of Austin, Texas, USA (see Fig. 1). There is a large amount of literature on engineering problems of heat exchangers. For more details and engineering computational analysis of complex heat exchangers we refer to [42–44]. Fouling is a major problem in heat exchanger design. Fouling is a general term that encompass the deposition of unwanted materials in the pipe surface, which eventually interfere in the heat exchanger performance during the operational lifetime [45–47]. We refer for example to Fig. 7 in [41] and to [45–47] regarding the effects of fouling.

The aim of this paper is not to address a particular heat exchanger problem but to show typical difficulties when dealing with a specific engineering problem. Thus, we are interested in computational predictions of the dependence of the fouling build up on the effectiveness of the heat exchanger, which is directly related to the so called thermal resistance R_f, a heat exchanger property that has to be computed. The major problem is that the available information needed for the prediction comes with many uncertainties. They have to be quantitatively characterized and transformed by the computational model

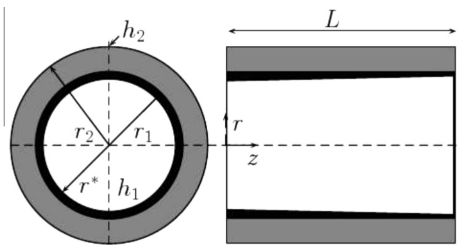

Fig. 1. The geometry of the pipe (gray) with fouling (black).

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