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KNOWLEDGE-BASED EXPERT SYSTEM FOR FOULING ASSESSMENT OF INDUSTRIAL HEAT EXCHANGERS

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Abstract—The paper emphasises the need for the development of the expert system as a tool for the mitigation of the fouling processes. Particular reference is given to the design margin lifetime assessment, fouling process control, fouling removal assessment and heat-exchanger safety by the expert system for industrial heat exchangers.

This paper presents the concept of a heat-exchanger on-line system. The heat-exchanger efficiency is defined by the NTU concept for the simple parallel co-current heat exchanger. The respective methodology is used for the description of the generic behaviour of the heat-exchanger system. Particular attention was paid to the recognition of those situations leading to the degradation of the efficiency of the heat exchanger. The paper describes the selection of the diagnostic variables and their on-line measurements, including the logging system for the monitoring and acquisition of the data.

The knowledge base is derived from the definition of the heat-exchanger efficiency. The approach presented is based on an object–attribute–value structured knowledge base. It includes hot and cold stream flow rate and hot and cold fouling thickness assessment. In this respect, particular attention was paid to the fouling process assessment and its effect on the efficiency degradation of the heat exchanger.

For the specific heat exchanger, the expert system assessment of different situations was shown with this approach.

Keywords—Expert system, knowledge-based system, fouling, heat exchangers, expert system development, heat-exchanger efficiency.

1. INTRODUCTION

Fouling in heat exchangers has been recognised as the main cause for the degradation of efficiency in industrial plants [1–3]. Its adverse effect is measured in billions of dollars every year, so any opportunity should be used for the mitigation or control of the fouling process. Difficulty in meeting this requirement poses a challenge to investigate the possibility of using some of the modern tools developed for information processing, in order to gain a qualitative and quantitative assessment of the fouling process.

As is known, in the design of heat exchangers the overall heat transfer coefficient plays the most important role in controlling the size of the heat exchanger. Fouling margins are introduced into the design, in order to safeguard the operation of fouled heat exchangers. Starting with clear surfaces the heat exchanger is oversized and during the operation, as fouling develops, it will reach its limitation and after this point the heat exchanger is not in a position to meet design requirements. So, it can be colloquially said that the design margin has its lifetime. The control of the lifetime of the design margin is one of the important requirements for the economically justified operation of the heat exchanger. For this reason, the margin consumption lifetime will be expressed as the respective economic value, in order to introduce direct economic parameters into the assessment of the fouling process. In this respect, the heat-exchanger fouling expert system can bring added value to the economy of heat exchangers.

There are different fouling processes, depending on flow, concentration and temperature field in the heat-exchanger channels [4–6]. In many plants the heat exchangers are operating under different stream inlet conditions leading to changes in the flow, concentration and temperature. As the fouling process may be sensitive to those changes, it is important for fouling process control to know the fouling process mechanisms, in order to take respective action for the mitigation of the adverse effects of the fouling process. For this reason, it is of paramount importance to be in a position to make an assessment of the type of fouling process which is taking place in the heat exchanger.

Particular attention has to be devoted to the economic evaluation of the fouling process. Each fouling situation in the heat exchanger can be assessed from an economic point of view, in order to obtain an economic value of the heat-exchanger degradation by the fouling process. In this respect, the heat-exchanger fouling expert system can be an efficient tool for the economic assessment of the type of fouling process.

There are numerous methods for the removal of fouling from the heat-exchanger surface. Their efficiency will depend on the technique and method used and the knowledge of the fouling process. It is of great importance for the assessment of the efficiency of the cleaning process to develop tools for cleaning control.

Every uncontrolled fouling process can cause a safety threat for the plant. It is of importance, particularly for those processes where the hazard can be significant, to monitor those limitations which are set as the safety marks for the plant. In this respect, the heat-exchanger fouling expert system can be used as the safeguard system, which may give advance warning of the action to be taken in order to mitigate adverse effects on the plant operation.

Even though designers are doing all kinds of optimisation, including second-law concepts, the operational analysis of the heat-exchanger efficiency is an important approach in justifying the total annual cost function of heat exchangers [7–9]. In this respect, it becomes of paramount interest to develop a procedure to deal with the on-line assessment of heat-exchanger operation.

It has been proved [10–12] that expert system logic is becoming an effective tool in the development of procedures to be used in the on-line assessment of the parameters leading to the degradation of the system. However, selection of the expert system domain is one of the important issues to be considered in the development of the expert system. In order to investigate the main concept of the expert system for heat exchangers, attention is focused on the fouling assessment expert system.

Commonly, the expert system reasoning procedure in a number of engineering systems is based on the objective–attribute–value scheme in the design of the knowledge base [13]. It has been proved to be an efficient tool in the design of the heat-exchanger fouling assessment expert system [14, 15].

2. EXPERT SYSTEM DOMAIN

It is known by definition that the heat-exchanger efficiency is

$$\epsilon = \frac{T_{c2} - T_{c1}}{T_{h1} - T_{c1}}\left(\frac{C_c}{C_{min}}\right), \tag{1}$$

where T_{c1}, T_{c2}—inlet and outlet cold stream temperatures, respectively; T_{h1}—inlet temperature of hot stream; C_c—thermal capacity of cold stream; C_{min}—smaller thermal capacity rate.

The heat-exchanger effectiveness is defined as the ratio of the actual heat transferred to the maximum possible amount of heat that could be transferred in an infinitely long heat exchanger.

From the energy balance the following efficiency for a parallel-flow heat exchanger is obtained:

$$\epsilon = \frac{1 - \exp\left[-N_A\left(1 + \frac{C_{min}}{C_{max}}\right)\right]}{\left(1 + \frac{C_{min}}{C_{max}}\right)}, \tag{2}$$

where C_{max}, C_{min}—maximum and minimum streams thermal capacity rates; C—stream thermal capacity rate;

$$N_A = \frac{AU}{C_{min}}; \quad C = Wc_p. \tag{3}$$

Neglecting the circular geometry of a thin tube, we will obtain that for $C_{min}/C_{max} = 1$,

$$\tfrac{1}{2}\ln(1 - 2\epsilon) = -N_A \tag{4}$$

or

$$\tfrac{1}{2}\ln(1 - 2\epsilon) = -\frac{A}{C_{min}}\left[\frac{1}{h_h} + \frac{\delta_h}{k_h} + \frac{\delta_m}{k_m} + \frac{\delta_c}{k_c} + \frac{1}{h_c}\right], \tag{5}$$

where h_h, h_c—heat-transfer coefficients on hot and cold stream sides, respectively; δ_h, δ_c—fouling-layer thickness on hot and cold stream sides, respectively; k_h, k_c—thermal conductivity of fouling layers; δ_m, k_m—tube wall thickness and thermal conductivity.

This proves that reduced efficiency is defined by the following set of parameters:

$$h_h, \delta_h, h_c, \delta_c,$$

assuming that δ_m, k_h, k_c and k_m are constant. If we introduce the fact that the heat transfer coefficients are proportional to the respective mass flow rates, it follows that the reduced effectiveness in steady-state operation of the heat exchanger is defined by the following set of diagnostic variables:

$$W_h, W_c, \delta_h, \delta_c.$$

The second group of diagnostic parameters could be obtained if we take into consideration the time change of the reduced effectiveness.

After differentiation of the expression for the efficiency for parallel flow, we will obtain

$$\frac{1}{(1-2\epsilon)}\frac{\mathrm{d}\epsilon}{\mathrm{d}t} = \frac{\mathrm{d}N_A}{\mathrm{d}t} - \frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{AU}{C_{min}}\right) = -\frac{1}{C_{min}}\left[\frac{1}{h_h} + \frac{\delta_h}{k_h} + \frac{\delta_m}{k_m} + \frac{\delta_c}{k_c} + \frac{1}{h_c}\right]. \tag{6}$$

If it is assumed that h_h, δ_h, h_c and δ_c are time-dependent variables then it follows that

$$\frac{\mathrm{d}N_A}{\mathrm{d}t} = \left(\frac{\partial N_A}{\partial h_h}\frac{\partial h_h}{\partial t}\right) + \left(\frac{\partial N_A}{\partial \delta_h}\frac{\partial \delta_h}{\partial t}\right) + \left(\frac{\partial N_A}{\partial \delta_c}\frac{\partial \delta_c}{\partial t}\right) + \left(\frac{\partial N_A}{\partial h_c}\frac{\partial h_c}{\partial t}\right), \tag{7}$$

where

$$\frac{\partial N_A}{\partial h_h}\frac{\partial h_h}{\partial t} = \frac{A}{C_{min}}\frac{1}{h_h^2}\frac{\partial h_h}{\partial t}K_1\frac{\partial h_h}{\partial t}$$

$$\frac{\partial N_A}{\partial \delta_h}\frac{\partial \delta_h}{\partial t} = \frac{A}{C_{min}}\frac{1}{\delta_h^2}\frac{\partial \delta_h}{\partial t} = K_2\frac{\partial \delta_h}{\partial t}$$

$$\frac{\partial N_A}{\partial \delta_c}\frac{\partial \delta_c}{\partial t} = \frac{A}{C_{min}}\frac{1}{\delta_c^2}\frac{\partial \delta_c}{\partial t} = K_3\frac{\partial \delta_c}{\partial t}$$

$$\frac{\partial N_A}{\partial h_c}\frac{\partial h_c}{\partial t} = \frac{A}{C_{min}}\frac{1}{h_c^2}\frac{\partial h_c}{\partial t} = K_4\frac{\partial h_c}{\partial t}. \tag{8}$$

Introducing the expression for the heat-transfer coefficient as a linear function of mass flow rate for the hot and cold streams and assuming that the changes in flow rate will be substantially smaller than the flow rate for each stream, we will obtain

$$\frac{\partial W_h}{\partial t}; \quad \frac{\partial W_c}{\partial t}; \quad \frac{\partial \delta_h}{\partial t}; \quad \frac{\partial \delta_c}{\partial t},$$

which are diagnostic variables of the heat-exchanger efficiency.

3. MONITORING SYSTEM FOR THE HEAT-EXCHANGER EFFICIENCY

As was shown, the heat-exchanger efficiency can be monitored by on-line measurement of the following parameters:

$$T_{h1}, T_{c1}, T_{c2}.$$

Besides these parameters, the diagnostic system for fouling assessment expert system should include W_h and W_c.

In order to ensure confidence in the measuring system of these parameters, it is necessary to introduce into the diagnostic system a validation element to the software, which checks every reading before it gets to the semantic processing of the signal.

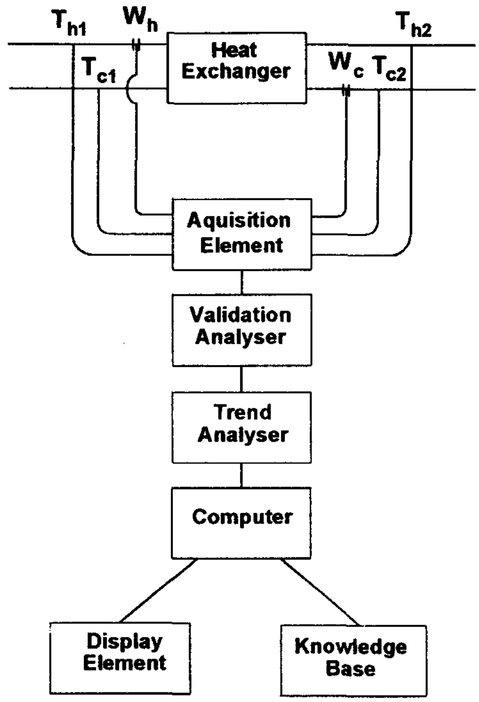

Fig. 1. Flow diagram of the on-line measurement and signal processing.

The diagnostic system also comprises a buffer for intermediate data storage and numerical data conversion into a semantic expression to be used in the expert shell processing. This element is normally included in the computer system but it is shown as a separate element.

Figure 1 shows the flow diagram for the on-line measurement and signal processing.

4. KNOWLEDGE-BASED SYSTEMS

The knowledge-based system of the heat-exchanger fouling assessment expert system has been associated with an evolutionary development process. A large part of expert system development has revolved around the development of the prototype systems. In this respect, the knowledge-based structure is strongly dependent on the reasoning strategy being adopted for the expert system. In this paper an approach to this problem will be demonstrated, based on the object–attribute–value structure of the knowledge base described by the efficiency model of the heat exchanger.

In the object–attribute–value knowledge-based system, the knowledge base is formed of three parts. One, comprises the facts to be used in the reasoning procedure of the expert shell. The second is rules describing procedural knowledge acquired to obtain an expected conclusion. The third part of the knowledge base includes a list of the expected situations to be obtained by each retrieval session of the system. This part will also include advice for the recommended action to be taken as an assessment of the measurement.

In this approach it was assumed that the object is a heat exchanger, not physically but in abstract meaning, having three attributes corresponding to the heat-exchanger fouling assessment domain, namely, efficiency, hot and cold stream flow and hot and cold stream side fouling. Efficiencies are used to define performance and represent the set of events expected to occur comprising all possible situations likely to occur. The hot and cold stream flow attributes describe the contribution of the efficiency change due to flow changes. The fouling attribute comprises changes resulting from the fouling thickness changes. Each object is accompanied by the respective attributes which are to describe its function and domain. Attributes are specified with the values and gradients to describe the state of the objects. Table 1 shows the object structure with its attribute and values.

Table 1.

Object attributes	EF	HS	CS	FH	FC
Values	RE	$W_h V$	$W_c V$	δ_h	δ_c
	1	1	1	0	0
	$1+\Delta$	$1+\phi^h$	$1+\phi^c$	1/2	1/2
	$1-\Delta$	$1-\phi^h$	$1-\phi^c$	1	1
Gradient	RCH	RW_h	RW_c	$R\delta_h$	$R\delta_c$
	0	0	0	0	0
	$\pm\xi_1$	$\pm\alpha_1^h$	$\pm\alpha_1^c$	β_1^h	β_1^c
	$\pm\xi_2$	$\pm\alpha_2^h$	$\pm\alpha_2^c$	β_2^h	β_2^c

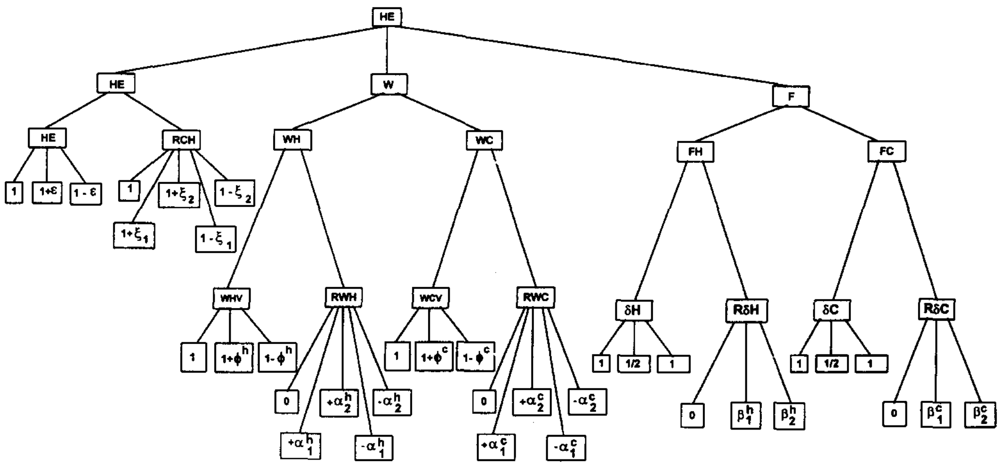

Fig. 2. List of objects—graphical presentation.

Individual values for each attribute of the specific object could be obtained by model simulation of the respective heat exchanger in the design of the expert system. Depending on the number of situations to be retrieved with the expert system, the number of the values for each attribute can be extended with the aim of gaining high accuracy in justification of the state of the heat exchanger.

If the presented data are taken as the facts in the LISP environment, then the list of the situations could be drawn. Figure 2 shows a graphical presentation of the lists to be obtained from the facts. Also, the structure of the knowledge base can be seen. The knowledge base comprises all possible situations within the domain of the selected parameters of the diagnostic variables.

In LISP language, the list of situations in the knowledge base is defined as

$$HE(EF(RE(1\ 1+\Delta\ 1-\Delta)RCH(0\ +\xi_1\ +\xi_2\ -\xi_1\ -\xi_2)))$$

$$(W(W_h(W_h V(1\ 1+\phi^h\ 1-\phi^h)RW_h(0\ +\alpha_1^h\ +\alpha_2^h\ -\alpha_1^h\ -\alpha_2^h)))$$

$$(W_c(W_c V(1\ 1+\phi^c\ 1-\phi^c)RW_h(0\ +\alpha_1^c\ +\alpha_2^c\ -\alpha_1^c\ -\alpha_2^c)))$$

$$(F(F^h(\delta_h(0\ \tfrac{1}{2}\ 1)R\delta_h(0\ \beta_1^h\ \beta_2^h)))$$

$$(F^c(\delta_c(0\ \tfrac{1}{2}\ 1)R\delta_c(0\ \beta_1^c\ \beta_2^c))).$$

The second part of the knowledge base is the production rule to be used in the representation of the strategy for the assessment of the set of diagnostic parameters. The production-rule format is

IF | premises | THAN | conclusion | ELSE | recommendation |.

As an example, in this paper only simple rules for the demonstration are given. Table 2 gives examples of production rules to be used in the fouling assessment expert system.

Table 2.

IF $RE = 1$ and $W_h V = 1$ and $W_c V = 1$ and $RCH = +\xi$ and $RW_h = 0$ and $RW_c = 0$ THAN Fouling begin
IF $RE = 1$ and $W_h V = 1$ and $W_c V = 1$ and $RCH = \pm\xi_1$ and $RW_h = \pm\alpha_1$ and $RW_c = 0$ THAN Flow change in CS
IF $RE = 1+\Delta$ and $W_h V = 1$ and $W_c V = 1+\phi_1^c$ and $RCH = 0$ and $RW_h = +\alpha_1$ and $RW_c = 0$ THAN Fouling begin
IF $RE = 1+\Delta$ and $W_h V = 1$ and $W_c V = 1$ and $RCH = 0$ and $RW_h = 0$ and $RW_c = 0$ THAN Heavy fouling
IF $RE = 1$ and $W_h V = 1$ and $W_c V = 1$ and $RCH = +\xi_1$ and $RW_h = 0$ and $RW_c = 0$ THAN Fouling diffusion controlled
IF $RE = 1$ and $W_h V = 1$ and $W_c V = 1$ and $RCH = +\xi_2$ and $RW_h = 0$ and $RW_c = 0$ THAN Fouling mechanically controlled

Table 3.

Fouling begin	Increased attention is required
Fouling diffusion controlled	Long-term process and slow development is expected If it will continue for . . . days it will cost . . . $/day
Heavy fouling	If it continues for . . . days, it will reach its limit Cleaning should be scheduled within . . . days
Cold side fouling	Increased attention on the cold side stream is needed
Hot side fouling	Increased attention on the hot side stream is needed

The third part of the knowledge base is the set of conclusions with related recommendations to be given to the users. It will include economic justification of the fouling states and will give an assessment of the forthcoming development. Table 3 gives some typical examples of the conclusions to be used in the heat-exchanger expert system.

5. CONCLUSIONS

The concept of the design of an expert system for fouling assessment in the heat exchangers demonstrated has shown the feasibility of this tool to be used to increase the efficiency and availability of the heat exchanger.

A knowledge-based expert system for fouling assessment based on the efficiency model is demonstrated. The object–attribute–value structure of the knowledge base has been used for the model facts organisation for the respective reasoning procedure to be adopted. It was shown that a sufficient number of situations could be generated and used in the assessment of the fouling process.

In particular, the example demonstrated, by its application in the fouling assessment of heat exchangers, shows that this technique can be extensively used in the assessment of heat-exchanger performance. Even though the example shown uses a simple-design heat exchanger, it was shown that the heat-exchanger expert system based on the knowledge-based paradigm could stimulate the further development of a number of specific designs of heat exchanger which require attention in operation.

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