A Confluence-Based Expert System for the Detection of Heat Exchanger Fouling

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Efficiency assessment of heat exchangers ensures appropriate use of the available energy. This article presents the concept of a heat exchanger on-line expert system based on qualitative reasoning. Using confluence of the heat exchanger effectiveness defined by the NTU (number of transfer units) concept for the simple parallel-stream heat exchanger, the methodology is developed to be used for the description of the generic behavior of the heat exchanger system. In this respect, particular attention was paid to the recognition of those situations leading to the degradation of the effectiveness of the heat exchanger. The article describes the selection of the diagnostic variables, and their on-line measurements including the logging system for monitoring and acquisition of the data.

For a specific heat exchanger, the expert system assessment was performed for a number of different situations. An appropriate diagnostic system in the specified time period produces a set of readings of the diagnostic variables, describing the state of the system. The set of diagnostic variables converted into the confluence parameters constitutes the qualitative description of the instantaneous state of the system. A retrieval strategy is used to find the corresponding state in the knowledge base with the set of the parameters describing the individual malfunction state of the system. Each malfunction state is accompanied by a recommendation for its correction specified by expert advice.

In many heat exchangers, fouling is an important problem that requires careful monitoring. In spite of precautions taken in the design of the heat exchanger, fouling is an unavoidable problem. Presently, designers are doing all kinds of optimization of heat exchangers. Second law analysis of heat exchanger effectiveness is the most powerful approach in justification of the total annual cost function of a heat exchanger [1–3]. In this respect it becomes of paramount interest to develop a procedure to deal with the on-line assessment of heat exchanger operation. In particular, in some heavy-duty operations, heat exchangers are a milestone of total system operation that require monitoring and assessment during on-line operation.

Heat exchanger effectiveness is the parameter that comprises all relevant effects that induce degradation of the availability cost of heat exchanger operation. On-line monitoring of the effectiveness is technically feasible with suitable instrumentation and logging system.

Expert system tools are becoming a very efficient means in the assessment of the functioning of a process system. Several studies [4–8] have demonstrated that expert system logic is becoming an effective tool for 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 specific concept of an

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or

$$\frac{dN_A}{dt}=\left(\frac{\partial N_A}{\partial h_h}\frac{\partial h_h}{\partial t}\right)+\left(\frac{\partial N_A}{\partial \delta_h}\frac{\partial \delta_h}{\partial t}\right)$$
$$+\left(\frac{\partial N_A}{\partial \delta_c}\frac{\partial h_c}{\partial t}\right)+\left(\frac{\partial N_A}{\partial h_c}\frac{\partial h_c}{\partial t}\right) \quad (9)$$

where

$$\frac{\partial N_A}{\partial h_h}\frac{\partial h_h}{\partial t}=\frac{AU^2}{C_{\min}}\frac{1}{h_h}\frac{\partial h_h}{\partial t}=K_1\frac{\partial h_h}{\partial t} \quad (10)$$

$$\frac{\partial N_A}{\partial \delta_h}\frac{\partial \delta_h}{\partial t}=\frac{AU^2}{C_{\min}}\frac{1}{k_h}\frac{\partial \delta_h}{\partial t}=K_2\frac{\partial \delta_h}{\partial t} \quad (11)$$

$$\frac{\partial N_A}{\partial \delta_c}\frac{\partial \delta_c}{\partial t}=\frac{AU^2}{C_{\min}}\frac{1}{k_c}\frac{\partial \delta_c}{\partial t}=K_3\frac{\partial \delta_c}{\partial t} \quad (12)$$

$$\frac{\partial N_A}{\partial h_c}\frac{\partial h_c}{\partial t}=\frac{AU^2}{C_{\min}}\frac{1}{h_c}\frac{\partial h_c}{\partial t}=K_4\frac{\partial h_c}{\partial t} \quad (13)$$

It is known that the heat transfer coefficient in a heat exchanger is a complex function of a number of variables dependent on the specific design of the heat transfer surface. As the first approximation in this analysis, a simple geometry of heat transfer surface will be assumed in order to overcome eventual problems with nonlinearity of the heat transfer coefficient dependence on the flow rate.

Introducing the expression for heat transfer coefficients as linear functions 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 obtain

$$\frac{\partial N_A}{\partial h_h}\frac{\partial h_h}{\partial t}=\Phi_1\frac{\partial W_h}{\partial t}\cdots\frac{\partial N_A}{\partial \delta_h}\frac{\partial \delta}{\partial t}=K_2\frac{\partial \delta_c}{\partial t} \quad (14)$$

$$\frac{\partial N_A}{\partial \delta_c}\frac{\partial \delta_c}{\partial t}=K_3\frac{\partial \delta_c}{\partial t}\cdots\frac{\partial N_A}{\partial h_c}\frac{\partial h_c}{\partial t}=\Phi_2\frac{\partial W_c}{\partial t} \quad (15)$$

where Φ_1, Φ_2, K_2, K_3 are constants to be determined for a specific heat exchanger and

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

are diagnostic parameters reflecting the change of heat exchanger effectiveness.

QUALITATIVE REASONING BASED ON A CONFLUENCE

In qualitative process analysis, the notion of a qualitative differential equation is called confluence [12, 14–16]. It was shown that confluence could be used in the definition of state for any physical system. Qualitative analysis is based on the behavioral description of the process in which, instead of continuous real-valued variables, each variable is described qualitatively, taking only a small number of values, usually $+, -, 0$. Thus, the main assessment tool is the qualitative differential equation, called a confluence. As can be seen in the derivation of the heat exchanger effectiveness, the confluence is

$$\Phi_1\frac{\partial W_h}{\partial t}+\Phi_2\frac{\partial W_c}{\partial t}+K_2\frac{\partial \delta_h}{\partial t}+K_3\frac{\partial \delta_c}{\partial t}$$
$$=\frac{1}{(1-2\epsilon)}\frac{\partial \epsilon}{\partial t} \quad (16)$$

Introduce

$$\frac{1}{(1-2\epsilon)}\frac{\partial \epsilon}{\partial t}=\Gamma \quad (17)$$

Then

$$\Phi_1\frac{\partial W_h}{\partial t}+\Phi_2\frac{\partial W_c}{\partial t}+K_2\frac{\partial \delta_h}{\partial t}+K_3\frac{\partial \delta_c}{\partial t}=\Gamma \quad (18)$$

Adopting the notation that $\partial/\partial t=\partial$, one obtains

$$\Phi_1\,\partial W_h+\Phi_2\,\partial W_c+K_2\,\partial\delta_h+K_3\,\partial\delta_c=\Gamma \quad (19)$$

so that the confluence is

$$\partial W_h+\partial W_c+\partial\delta_h+\partial\delta_c=\Gamma_0 \quad (20)$$

If it is accepted that the four variables could assume the following values,

$$\partial W_h=+,-,0 \qquad \partial\delta_h=+,\ 0$$
$$\partial W_c=+,-,0 \qquad \partial\delta_c=+,\ 0 \quad (21)$$

then the number of possible states for Eq. (20) is as given in Tables 1, 2, and 3. Tables 1, 2, and 3

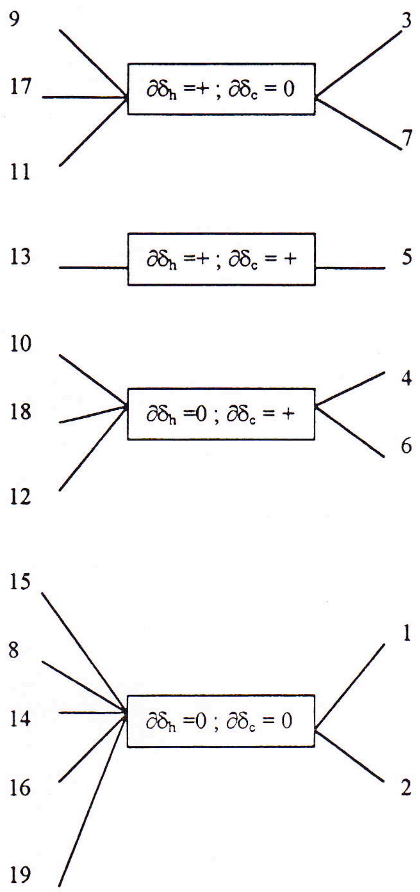

Figure 1 State diagram.

The second part of the knowledge base is a set of conclusions with related recommendations to be given to the user. It will include economic evaluators of the consequences of the fouling states and will give possibilities for the assessment of forthcoming development. Also, it is expected that in the future development of expert systems there will be a pattern recognition procedure that will be able to forecast both short- and long-time behavior of heat exchangers. This includes displaying messages to the user and imposing emergency procedures if the situation warrants.

MONITORING SYSTEM FOR HEAT EXCHANGER EFFECTIVENESS

Heat exchanger effectiveness can be monitored by on-line measurement of the following parameters:

$$T_{h1}, T_{h2}, T_{c1}, T_{c2}$$

Beside these parameters, the diagnostic system for the fouling assessment expert system should include:

$$W_h, W_c$$

In order to ensure confidence in the measurements, it is necessary to introduce a validation element in the diagnostic system, which checks every reading it enters before the semantic processing.

Diagnostic systems also comprise 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 is shown as a separate element in Figure 2.

SIGNAL PROCESSING AND ANALYSIS

Qualitative reasoning is commonly based on the signal of measurements of the variables. In order

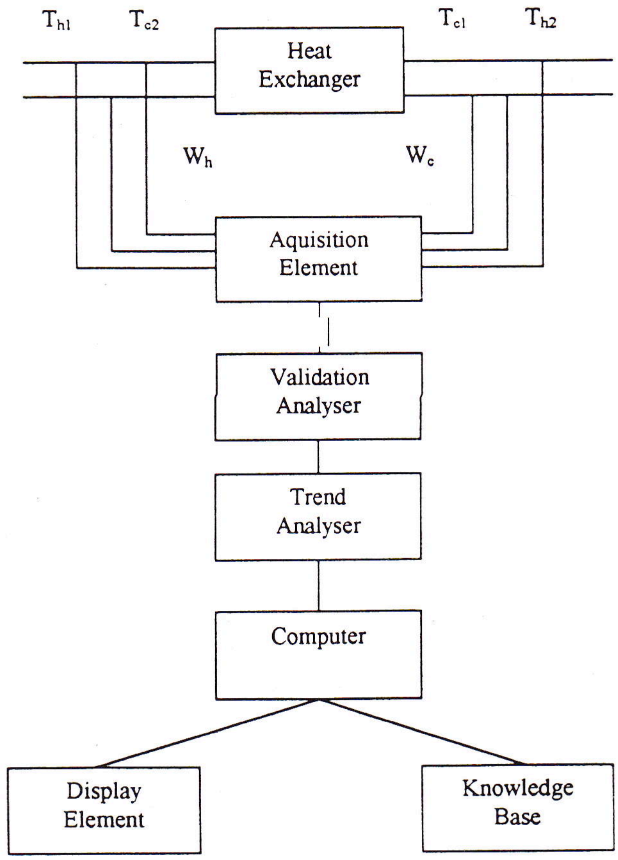

Figure 2 Flow diagram for on-line measurement and signal processing.

CONCLUSIONS

The conceptual design of an expert system for fouling assessment in a heat exchanger has shown the feasibility of this tool to increase the effectiveness and availability of the heat exchanger.

The technique of sign analysis based on qualitative reasoning introduced by the concept of confluence with trend analysis of the variable measurements shows a new possibility in the assessment of operational parameters of engineering systems. In particular, the example demonstrated by application to the fouling assessment of a heat exchanger suggests that this technique can be used in the assessment of heat exchanger performance. In spite of the fact that the example presented in this article relates to a simple heat exchanger design, it was demonstrated that a heat exchanger expert system based on qualitative reasoning may be further developed for other designs.

NOMENCLATURE

A	heat transfer surface
C_c	thermal capacity of cold stream
C_{max}, C_{min}	maximum and minimum stream thermal capacity rates
h_h, h_c	heat transfer coefficients on the hot and cold sides, respectively
k_h, k_c	thermal conductivities of fouling layers on the hot and cold sides of the heat transfer surface, respectively
K_1	$= \frac{AU^2}{C_{min}} \frac{1}{h_h^2}$
K_2	$= \frac{AU^2}{C_{min}} \frac{1}{k_h}$
K_3	$= \frac{AU^2}{C_{min}} \frac{1}{k_c}$
K_4	$= \frac{AU^2}{C_{min}} \frac{1}{h_c^2}$
N_A	number of transfer units defined by Eq. (2)
R_h, R_c	proportionality constants for hot and cold stream heat transfer coefficients, respectively
t	time
T_{h1}, T_{h2}	inlet and outlet temperatures of the hot stream, respectively
T_{c1}, T_{c2}	inlet and outlet temperatures of the cold stream, respectively
U	overall heat transfer coefficient
Γ, Γ_0	defined by Eqs. (17) and (20), respectively
W_h, W_c	mass flow rates of the hot and cold streams, respectively
δ_h, δ_c	fouling layer thicknesses on the hot and cold sides, respectively
δ_m, k_m	tube wall thickness and thermal conductivity, respectively
Δ	incremental change of the diagnostic variables
ϵ	heat exchanger effectiveness defined by Eq. (2)
ζ	uncertainty margin of diagnostic variables
Φ_1	$= K_1 R_1$
Φ_2	$= K_2 R_2$

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