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Tuning Parameters of PID Controllers for the Operation of Heat Exchangers under Fouling Conditions

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The present paper is an extension of the work presented by authors at SDEWES2015 conference, where changes in the dynamic behaviour of shell-and-tube heat exchangers induced by fouling build-up were studied. A mathematical model was proposed of transient heat exchange with the influence of thermal resistance of fouling taken into account. Next a mathematical model of the entire heat exchanger was implemented and simulations were carried out using Simulink in MATLAB environment. The model was validated using data records acquired during 3 years of operation of a heat exchanger network coupled with a Crude Distillation Unit (CDU). Using the validated dynamic model, one can simulate the behaviour of a heat exchanger together with its PID control loop and investigate the influence of fouling build-up on specific indexes of quality of operation. A simulation study was carried out on selected PID-controlled exchangers operated in a heat exchanger network coupled with a CDU rated 220 kg/s crude oil. For different periods of uninterrupted exchanger operation, that is, at different values of the thermal resistance of fouling, tuning parameters were determined using the Ziegler-Nichols method. It was found that the optimal values of tuning parameters changed when the thermal resistance of fouling was changed. However, oscillations remained in the characteristics of some controlled exchangers indicating that the new values of tuning parameters determined by the simple Ziegler–Nichols method were ineffective. In the present work, to improve the quality indices of the exchangers control under fouling conditions, a more advanced method of the optimization of controller tuning is presented using Signal Constraint block in MATLAB/SIMULINK.

1. Introduction

It belongs to industrial practice that the operation of a heat exchanger may be affected by fouling which builds up on the heat transfer surface. In a real-life plant, possible consequences of fouling include burning extra fuel to compensate for reduced heat recovery, reducing plant output when the exchangers are cleaned and generating costs of cleaning interventions. In recent years, various approaches to the mitigation of fouling effects in industrial heat exchangers and exchanger networks have been reported in the literature.

Apart from fouling-induced reduction of steady-state heat recovery (Liu et al., 2015), transient states of heat exchangers (Ansari and Mortazavi, 2006) and inefficient control of both individual exchangers (Khare and Singh, 2010) and entire networks (Varga et al., 1995) may also have a detrimental effect on the overall HEN performance. Dobos and Abonyi (2011) proposed a tuning procedure for application to a non-linear model predictive controller (NMPC) whose control goal is specified. The performance of the controller is characterized by an economic cost function based on pre-defined ranges of operation parameters. A methodology based on the experiment-design approach is applied to tune the model predictive controller so that it can attain the optimum performance. The efficiency of the proposed methodology is proven throughout a case study on a simulated NMPC-controlled district heating network.

However, papers devoted to the role of fouling in control issues are rare and limited in scope. The present authors seeing the shortcomings in the literature, hypothesized that the influence of fouling deposition in heat exchangers on the quality of their control should be studied with the aim of describing fouling effects

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quantitatively. In the present paper, as an extension of the work (Trafczynski et al., 2015), a control-theory based approach to identify and evaluate the influence of fouling on the dynamic behaviour of PID-controlled heat exchangers is discussed in detail, and the results of a case study are presented.

2. Fouling impact on the dynamics of PID-controlled heat exchangers

For several decades since Ziegler and Nichols proposed their first PID tuning method, the proportional-integral-derivative (PID) controllers are used in many industrial control systems (e.g., temperature control at heat exchanger outlet, Figure 3(a). On the one hand, PID controller structure is simple and its functioning principle is easier to understand than those of other advanced controllers. For example; Ganji et al. (2013) surveyed different conventional and intelligent controllers implemented with a clear objective to control the outlet fluid temperature of shell and tube heat exchanger system. Sivakumar et al. (2012) designed the temperature control system of the shell and tube heat exchanger by combining fuzzy and PID control methods. Oravec et al. (2016) presented novel robust Model-based Predictive Control (MPC) of a heat exchanger. On the other hand, the performance of simple controllers is satisfactory in many applications. For these reasons, most controllers used in industry are of PID type (Khare and Singh, 2010).

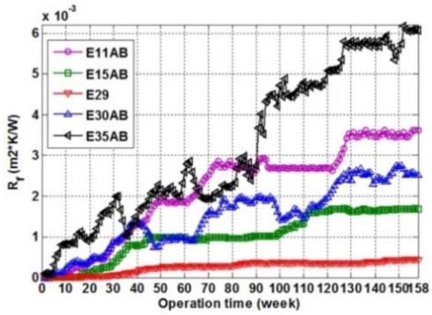


Figure 1: Fouling factor versus time during three years of operation

Following its validation, the dynamic heat-exchanger model was adopted in simulating the operation of PID-controlled heat exchangers (Trafczynski et al., 2015). In order to investigate the influence of fouling build-up on the dynamic behavior of the exchangers and on the quality of their control, five different exchangers were selected from a real-life heat exchanger network coupled with a CDU rated 220 kg/s of crude oil. Their characteristics were studied at different stages of fouling build-up, that is, after one, two and three years of the continuous operation of the exchanger unit. The relationships between the thermal resistance of fouling R_f and time (Figure 1) were determined using a method described in (Markowski et al., 2013). E29 is a single exchanger while the other units comprise two exchangers connected in series.

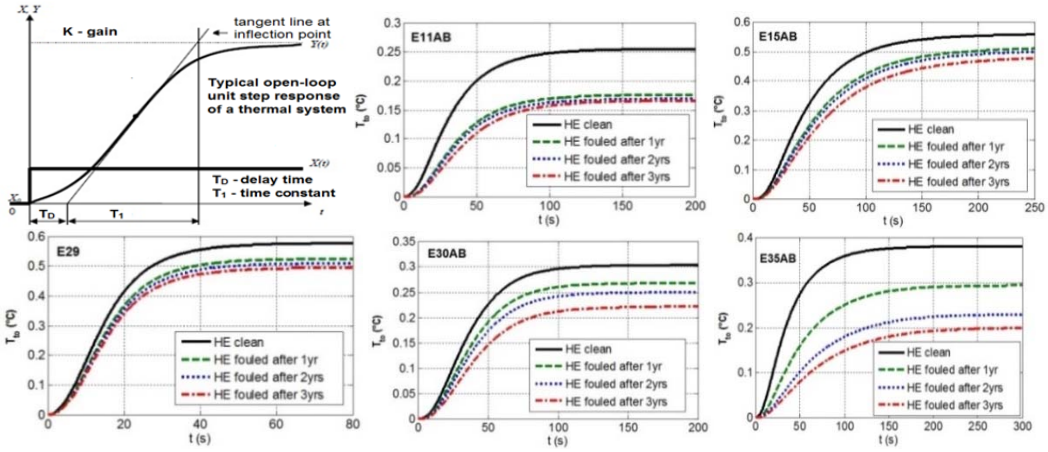


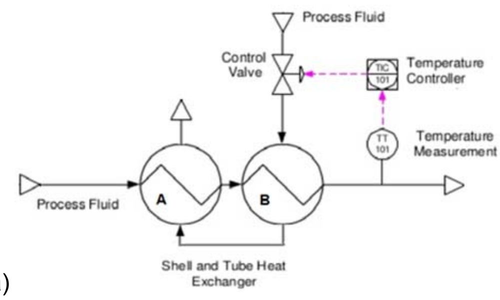
Figure 2: Open-loop responses of the heat exchangers to +5 % step change in the shell side flowrate

2.1 Heat exchanger dynamic analysis

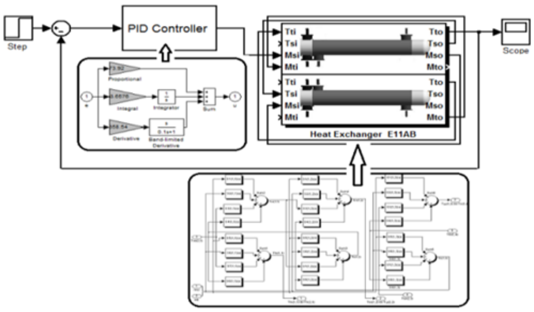
The simulations for the different periods of a heat exchanger operation time were carried out in Simulink and the simulation results have been obtained. In Figure 2, the open-loop responses of the heat exchangers models are plotted for a step upset +5 % in the shell side flowrate. It can be seen in the open-loop responses that in each of the studied exchangers, changes are visible in the values of gain K, delay time T_D and time constant T_1. These are the consequences of fouling build-up on the exchangers' heat transfer surfaces. While the changes in the delay time are insignificant, the increased time constants and reduced gain values may impair the quality of PID control considerably. In order to prevent that from happening, it is advisable to investigate all the three components of the tuning of each PID controller (K_p, K_i, K_d, that is, gain values in the proportional, integral and derivative components) and to check the resulting transient responses.

2.2 Closed-loop control analysis

Figure 3(b) represents the results of Simulink modelling of a heat exchanger unit including feedback PID controller. For each of the studied operation stages, the values of tuning parameters of PID controller were determined using Ziegler and Nichols (1942) method aimed at ensuring correct exchanger operation. The obtained results (see Table 1) indicate that to compensate for fouling build-up on the heat transfer surfaces, periodic corrections of the tuning of PID controllers are required. For each of the studied exchangers, the recommended values of gains K_p, K_i, K_d change considerably between the different stages of operation. In order to evaluate possible adverse effects of fouling on the control quality, studies of transient responses of the control system are needed. Regarding linear control systems, their transient characteristics are usually evaluated by studying the responses to a unit input signal 1(t). The upper left part of Figure 4 illustrates a typical response of a linear system of 2nd order represented by the temperature control system of a heat exchanger. The other diagrams in Figure 4 depict simulated responses of the studied heat exchanger units in four different stages of their operation, that is, with the heat-transfer surface either clean, or fouled after one, two and three years of continuous operation, however with the values of PID tuning parameters assumed in accordance with Table 1 data for clean exchangers.



(a)



(b)

Figure 3: Scheme of a heat exchanger with PID temperature control – (a), Simulink model of a heat exchanger system with feedback PID controller – (b)

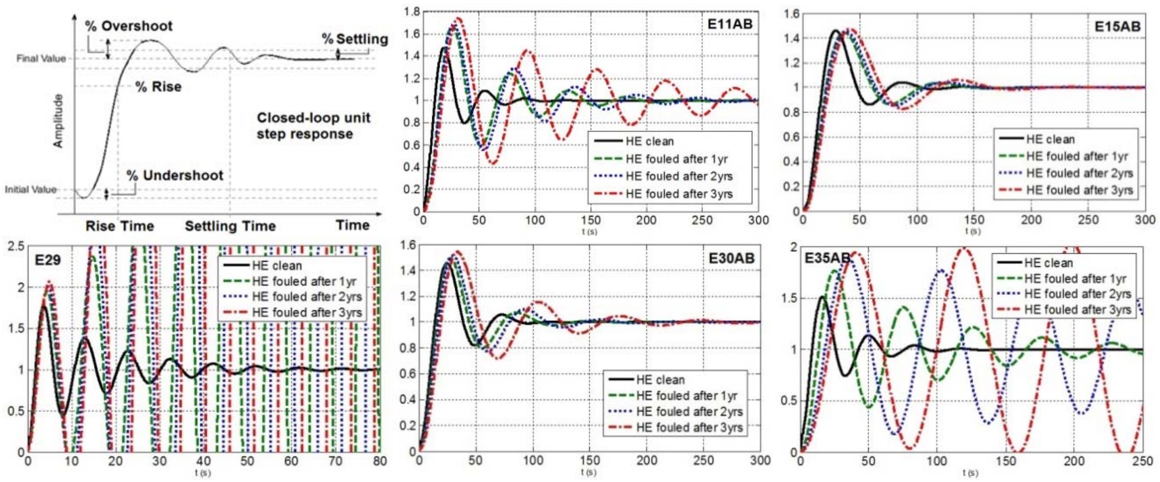


Figure 4: Closed-loop step responses of heat exchanger models without adjustment of PID tuning parameters

As can be seen in the transient responses obtained for the consecutive stages of heat-exchanger operation, the build-up of fouling is accompanied by deteriorating control-quality indices including overshoot, rise time and settling time: their values are increased. Regarding heat exchangers E29 and E35AB, fouling build-up would lead to instability of the controllers unless their tuning parameters were adjusted.

Table 1: Values of PID controller parameters obtained using Ziegler-Nichols method

Heat exchanger		E11AB	E15AB	E29	E11AB	E15AB
	PID parameters					
Without fouling	K_p	69.84	2.436	91.56	38.24	32.47
	K_i	4.581	0.104	29.23	1.924	2.371
	K_d	255.5	13.75	68.83	182.3	106.7
With fouling after one year of operation	K_p	70.74	3.384	116.3	41.49	35.84
	K_i	3.594	0.143	35.11	1.975	1.945
	K_d	334.2	19.23	92.56	209.3	158.5
With fouling after two years of operation	K_p	73.92	3.541	126.9	44.09	51.14
	K_i	3.658	0.148	37.91	2.029	2.398
	K_d	358.5	20.38	101.9	230.1	261.8
With fouling after three years of operation	K_p	88.68	3.876	138.2	49.73	62.19
	K_i	4.178	0.157	40.91	2.157	2.714
	K_d	451.7	22.95	112.1	275.2	342.1

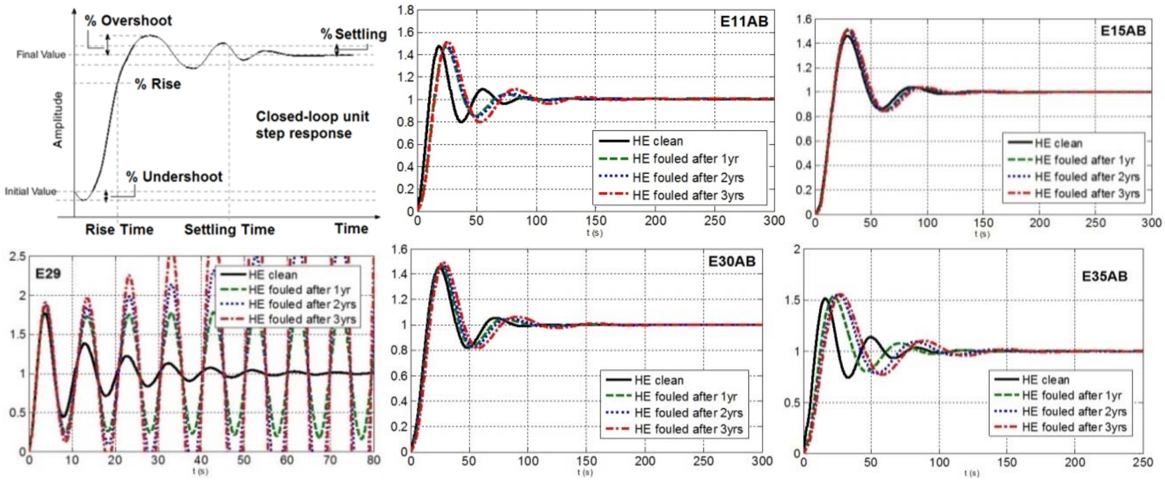


Figure 5: Closed-loop step responses of heat exchanger models after adjustment of PID tuning parameters

Figure 5 depicts simulated step responses of the studied heat exchanger units with their controller tuning parameters adjusted in accordance with the data shown in Table 1. These characteristics indicate that if the real-life controller tuning was adjusted to fit the requirements of the consecutive stages of fouling build-up, then the indices of control quality would not be adversely affected. It can be seen that changed tuning parameters of the controllers of exchangers E15AB and E30AB resulted in stabilizing the quality indices, while in the case of exchangers E11AB and E35AB, the quality indices were changed insignificantly. However, oscillations remained in the characteristics of exchanger E29; this appears to indicate that the new values of tuning parameters determined by the simple Ziegler–Nichols method were ineffective. Most probably, to improve the quality indices of E29 control, a more advanced method of the optimization of controller tuning would be required.

3. The optimal tuning parameters of a PID controller for the heat exchangers under fouling conditions

Seeing the problem with optimal tuning of PID controllers for heat exchangers under fouling conditions, the authors proposed to use Signal Constraint block in MATLAB/SIMULINK for the optimization of PID controller settings (Figure 6(a)). Prior to optimization, it is necessary to adjust constraint bounds in the Signal Constraint block constraint window (Figure 6(b)) and to declare tunable variables (K_p, K_i, K_d) using the Optimization Parameters dialog box. For each heat exchanger the constraint bounds can be set as follows: % Overshoot – max 20 %, % Undershoot – max 2 %, % Rise – 90 %, % Settling – 5 %, Rise Time – max 20 s, Settling Time –

max 75 s. After that, upon starting the optimization, the Signal Constraint block automatically converts the constraint bound data and tunable variable information into a constrained optimization problem, and invokes the Optimization Toolbox specific routine that adjusts the tunable variables in an attempt to better satisfy the constraints on system signals defined by the Signal Constraint block main interface. The specific routine solves the constrained optimization problems using the sequential quadratic programming (SQP) algorithm and quasi-Newton gradient search techniques. In short, the optimization problem formulated by the Signal Constraint block minimizes the maximum constraint violation. The number of iterations necessary for the optimization to converge and the final values of the tunable variables depend not only on the details of the problem to be solved but also on the characteristics of the computer system.

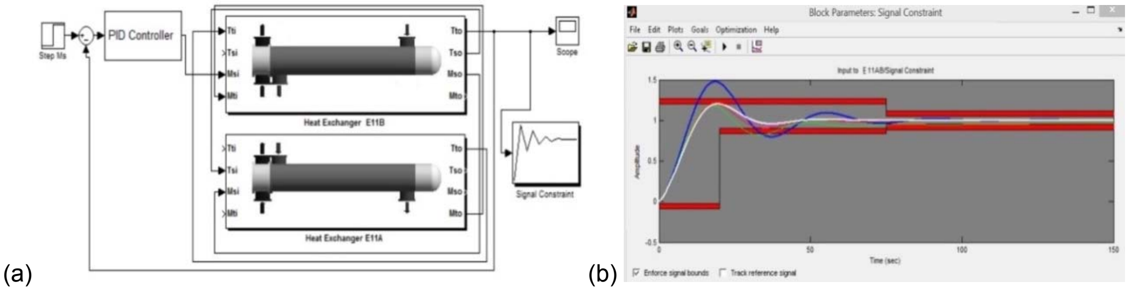


Figure 6: Simulink model of a heat exchanger system with feedback PID controller and Signal Constraint block – (a), Signal Constraint block constraint bounds figure – (b)

Table 2: Optimal values of PID-controller parameters obtained using Signal Constraint block in Simulink

Heat exchanger	PID parameters	E11AB	E15AB	E29	E11AB	E15AB
Without fouling	K_p	53.78	2.299	1.144	31.62	25.92
	K_i	1.785	0.034	0.178	0.814	0.395
	K_d	260.5	13.76	0.001	183.7	110.7
With fouling after	K_p	53.77	2.479	1.382	31.62	25.92
one year of	K_i	1.416	0.042	0.192	0.808	0.386
operation	K_d	260.5	13.78	0.003	183.7	110.7
With fouling after	K_p	53.77	2.765	1.465	31.62	30.44
two years of	K_i	1.394	0.034	0.197	0.808	0.416
operation	K_d	260.5	13.94	0.005	183.7	139.3
With fouling after	K_p	50.49	3.055	1.554	33.28	39.47
three years of	K_i	1.449	0.038	0.201	0.859	0.479
operation	K_d	285.7	17.01	0.006	212.6	216.2

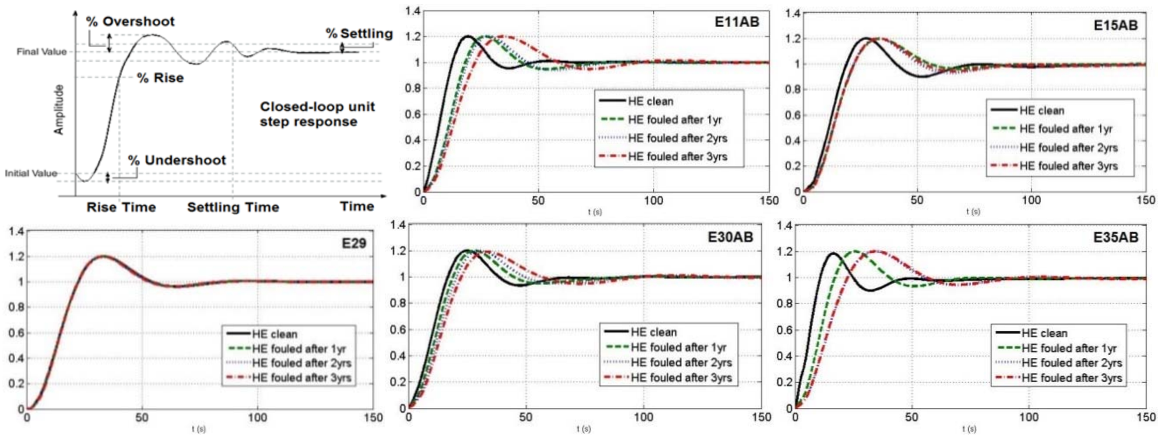


Figure 7: Closed-loop step responses of heat exchanger models after adjustment of optimal PID tuning parameters

In Table 2, the optimum values of PID-controller parameters for the studied heat exchanger units are listed. Figure 7 depicts simulated step responses of the exchangers with their controller settings adjusted in accordance with the data shown in Table 2.

4. Conclusions

Using Simulink-Matlab software, a validated dynamic model of shell-and-tube heat exchanger was applied in simulating the operation of PID-controlled exchanger units. A control-theory based approach was proposed for the identification and evaluation of the influence of fouling on the dynamic behavior of heat exchangers and on the quality of their control. It was shown that in the consecutive stages of exchanger operation affected by fouling build-up, appropriate controller tuning could be determined by using Signal Constraint tool.

The dynamic exchanger model was applied to a case study on selected temperature-controlled heat exchanger units operated in a heat exchanger network coupled with a CDU rated 220 kg/s of crude oil. The simulated step responses proved that to compensate for fouling build-up and to prevent the indices of control quality from deteriorating, periodic adjustments of the tuning of PID controllers were needed.

Overall, the presented results indicate that if the thermal resistance of fouling is increased, unchanged parameters of controller tuning can lead to oscillations of the controlled temperature, too slow response to set-point changes and the risk of significant – possibly dangerous – temperature overshoot, especially during the execution of start-up procedures. By adjusting the optimal values of proportional-integral-derivative gains K_p, K_i, K_d, these adverse effects of fouling can be prevented. For a given value of the thermal resistance of fouling, appropriate gain values can be determined using the dynamic model of the heat exchanger and the suitability of these values can be tested by simulation. The proposed approach can be applied in industrial decision-making related to the operation of PID-controlled heat exchanger networks.

In future research, drawing conclusions from the results obtained up to now, the present authors intend to develop a method for evaluating the magnitude of energy losses that may result from insufficient quality of heat-exchanger control caused by fouling build-up. The importance of this research topic is underscored by the fact that estimated 80 % of industrial heat exchangers equipped with PID controllers are operated either in manual mode, or using default values of the tuning parameters of their controllers.

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