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Gain-Scheduled Control of Counter-Current Shell-and-Tube Heat Exchangers in Series

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Gain scheduling is one of the control approaches that improve control of nonlinear processes. It involves tuning of controller parameters as a process passes from one operating range to another. In this way, the controller gains are better aligned with the nonlinear dynamics of the process and the linear nature of the conventional PID controllers is overcome. In this study, the gain-scheduled PID control is proposed for a heat exchanger network composed of five counter-current shell-and-tube heat exchangers in series, in which kerosene coming from a distillation unit in a refinery is cooled. Simulation results show that the gain-scheduled PID controller ensures better control performance as well as energy savings in comparison with conventionally tuned PID controllers.

1. Introduction

Heat Exchangers (HEs) and Heat Exchanger Networks (HENs) are often used across process industries, and as they are energy intensive processes, their effective and safe operation is important. Nemet et al. (2017) proposed a synthesis of safer HENs performing a risk assessment during the synthesis. The results confirmed that a significant increase of safety can be achieved with a minor economic expense. Bakar et al. (2017) addressed the problem of interaction between controller design and economic design. They implemented sensitivity analysis to measure the effect of disturbances on controlled variables or operational warnings, and they confirmed that all, the design, economy, and sensitivity criteria are important to obtain the best HEN. Sun et al. (2017) proposed coordination of bypass control and economic optimisation for HEN with stream splits and showed that bypass control is uneconomic without considering the economic performance. Nowadays, the advanced control strategies are often implemented in HE or HEN control to improve performance and to save energy. Vasičkaninová et al. (2017) designed Neural-Network-based Predictive Control (NNPC) for the counter-current HEs in series. The advanced control strategy led to coolant savings. Bakošová et al. (2017) designed and compared the robust Model-based Predictive Control (MPC) with integral action and the NNPC implemented on a tubular HE. Simulation results confirmed that improvements of the closed-loop control performance and energy savings were achieved in comparison with the conventional PID control. Vasičkaninová and Bakošová (2015) developed the strategy that uses a neural network predictive controller and a fuzzy controller in the complex control structure with an auxiliary manipulated variable. Adding the auxiliary fuzzy controller to the main neural network predictive controller improved the control performance of a tubular HE as well as the respond time. Gu et al. (2017) presented a dynamic flexible design methodology implemented by following stochastic disturbances. The methodology gives certain over-synthesis degree and can be the basis of integration of dynamic flexible synthesis and advanced control designs.

Gain Scheduling (GS) is a control approach that is commonly used for control improvement of nonlinear processes. It involves tuning of controller parameters as a process passes from one operating range to another. In this way, the controller gains are better aligned with the nonlinear dynamics of the process and the linear nature of the conventional PID controllers is overcome. Veselý and Ilľka (2013) addressed the problem of the gain-scheduled controller design which ensured the closed-loop stability and guaranteed cost for all changes of the scheduled parameter. The proposed procedure was based on the Lyapunov theory of stability. A robust PID controller and a gain-scheduled PI controller are designed in de Oliveira and Karimi (2012) for the temperature

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control in condensing boilers. According to their results, the closed-loop performance can be improved by using the gain-scheduled strategy, where the gains of the controller are a polynomial function of the water flow rate. Zhao and Nagamune (2017) presented an approach to switching Linear Parameter Varying (LPV) controllers considering uncertainties in the measurement of scheduling parameters. Bojan-Dragos et al. (2017) developed a gain-scheduled design procedure for PID controllers. The strategy was experimentally verified on control of a magnetic levitation system and overcame the state feedback control and conventional PID control. Krhovják et al. (2017) used GS strategy for control of a neutralization process. Controller parameters were scheduled as functions of the reference variable, and a single gain-scheduled controller was obtained.
Although there are a lot of applications of gain-scheduled controllers, it is still important to study this control approach from several points of view, i.e. control performance improvement, safety enhancement and energy savings. This study aims to show that gain-scheduled control improves control performance as well as saves energy in comparison with conventional PID control. The gain scheduling control is proposed for a simple HEN composed of five counter-current shell-and-tube heat exchangers in series in which kerosene, coming from a distillation unit in a refinery is cooled. As each heat exchanger in the network has nonlinear and asymmetric behaviour, the conventionally tuned PID controllers do not ensure satisfactory control performance. One way for improvement of the control performance and increase of the energy savings is using the gain-scheduled PID controllers. The advantages of this approach in comparison with the advanced control strategies are the simpler design, the lower computational burden and the possibility to use PID controllers.

2. Gain-scheduled controller design

Gain Scheduling (GS) is an important technique that enables to improve conventional PID control. GS deals with more complex characteristics, such as nonlinear process behaviour, asymmetric behaviour or time-varying features (Rugh and Shamma, 2000). The gain-scheduled controller is a controller whose gains are automatically adjusted as a function of time, operating conditions, or plant parameters. Gain scheduling is a widely used control strategy for processes whose dynamics change with time or operating conditions. These processes can be represented as linear parameter-varying (LPV) systems (Shamma, 2012) or various classes of nonlinear systems. The gain-scheduled control system is the feedback control system in which the gain-scheduled controller parameters are automatically tuned using a feed-forward gain scheduler by monitoring operating conditions (Figure 1).

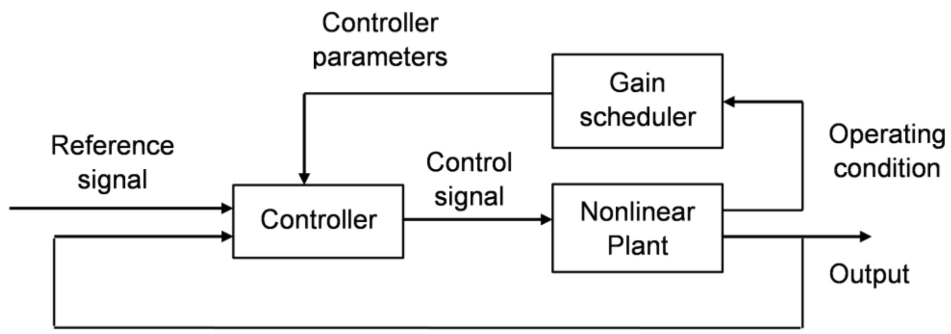

Figure 1: Gain-scheduled control system

In the gain-scheduled controller, the scheduled gains are functions of the scheduling variables, σ. For example, the gain-scheduled PID controller has the form Eq(1), where k_p, k_i, k_d are the proportional, integral and derivative gains and s is the Laplace transform argument:

$$C(s,\sigma)=k_p(\sigma)+\frac{k_i(\sigma)}{s}+k_d(\sigma)s \tag{1}$$

Tuning the GS controller requires determining the functions $k_p(\sigma)$, $k_i(\sigma)$ and $k_d(\sigma)$ that yield the best system performance over the operating range of σ values. However, it is not easy to tune arbitrary functions.
Therefore, it is necessary either to consider the function values at only a finite set of points or to restrict the generality of the functions themselves.
The gain scheduling design process can be summarized in the following steps:

- select a set of equilibrium points to cover the supposed operating range
- linearize the plant around each equilibrium point
- design a linear controller for each linearization, i.e. for each equilibrium point

- schedule the set of linear controllers, i.e. schedule the set of the controller gains

Since the local linear controllers are based on the linear time-invariant approximations of the original nonlinear system, the design guarantees that at each local operating point, the closed loop system is locally stable with guaranteed robustness and achieves the desired performance.

3. Simulations and results

3.1 Process description

Consider five identical counter-current shell-and-tube HEs in series (Figure 2). Kerosene that comes from a distillation unit flows in the inner tubes, and cooling water flows in the shell of each heat exchanger. The heat exchangers and the inner tubes are made of steel. The temperature of the outlet stream of kerosene from the 5th heat exchanger is the controlled output and volumetric flow rate of the inlet stream of cold water into the 5th heat exchanger is the control input. The objective is to decrease the kerosene temperature to the reference value and to decrease the cooling water consumption.

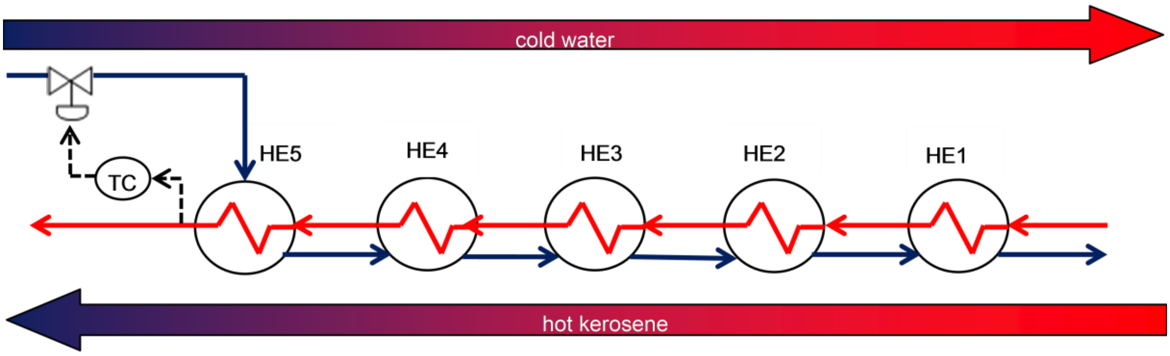

Figure 2: Scheme of counter-current shell-and-tube heat exchangers in series

Parameters of each heat exchanger in the HEN are presented in Table 1. Here, n is the number of the HE's tubes, l is the length of the HE, A is the heat transfer area, U is the overall heat transfer coefficient, d_{1in} is the inner diameter of the tube, d_{1out} is the outer diameter of the tube, d_{2in} is the inner diameter of the shell, ρ is the density and c_p is the specific heat capacity. The subscripts 1, 2 indicate the cold and the hot fluid, respectively. Ten first-order nonlinear ordinary differential equations represent a simplified nonlinear dynamic mathematical model of the HEN (Oravec et al., 2016).

Table 1: Parameters of heat exchangers

Variable	Unit	Value	Variable	Unit	Value	Variable	Unit	Value
n	1	40	d_{1in}	m	0.019	c_{p1}	J kg^{-1} K^{-1}	4.186
l	m	6	d_{1out}	m	0.025	c_{p2}	J kg^{-1} K^{-1}	2.140
A	m^2	16.6	d_{2in}	m	0.414	ρ_1	kg m^{-3}	980
U	J s^{-1} m^{-2} K^{-1}	482.17				ρ_2	kg m^{-3}	810

3.2 Control of the heat exchangers

Conventional PID controllers are described by the transfer function in Eq(2)

$$C(s) = k_p\left(1 + \frac{1}{t_i s} + t_d\right) = k_p + \frac{k_i}{s} + k_d s \tag{2}$$

where k_p, k_i and k_d are the proportional, integral and derivative gains, t_i *is* the integral time, and t_d *is* the derivative time. The PID controllers were tuned using the Cohen-Coon tuning rules and the Chien-Hrones-Reswick tuning method for 0 % overshoot (Ogunnaike and Ray, 1994).
For the conventional PID controller design, the model of the HEs was identified using the step-response-based method (Mikleš and Fikar, 2007) in the form of the n^{th} order plus time delay transfer function

$$S = \frac{K}{(Ts+1)^n} e^{-Ds} = \frac{-48}{(198s+1)^2} e^{-3s} \tag{3}$$

where K is the gain, T is the time constant and D is the time delay.

The PID controller parameters obtained using the Cohen-Coon and Chien-Hrones-Reswick formulas are in Table 2.

Table 2: Parameters of the conventionally tuned PID controllers

Tuning rules	k_p	k_i	k_d
Cohen-Coon	-0.2723	-0.1238	-0.0906
Chien-Hrones-Reswick	-0.8250	-0.2500	-0.0206

3.3 Gain-scheduled PID control of the heat exchangers

The nonlinear model of the considered HEN that had the form of ten nonlinear differential equations was linearized at various steady-state operating points. The output of the nonlinear as well as the linearized mathematical model of the HEN is the temperature of the outlet stream of kerosene from the 5th heat exchanger. The nonlinearity of the HEN yields different linearized dynamics at different output temperatures of kerosene. The lookup table was created (Table 3) that associates the specified output temperatures with the corresponding PID gains in order to implement them in the gain-scheduled control configuration. From the GS viewpoint, the step changes of the reference signal require new calculations of the process's equilibrium point, and the change of the controller parameters is needed always when the step change of the reference value occurs.

Table 3: Parameters of the gain-scheduled PID controllers

Temperature (K)	$k_p(\sigma)$	$k_i(\sigma)$	$k_d(\sigma)$
303	-0.4290	-0.0830	-0.3340
313	-0.0948	-0.0195	-0.0716
323	-0.0451	-0.0094	-0.0334
333	-0.0365	-0.0063	-0.0106
343	-0.0215	-0.0046	-0.0098
353	-0.0164	-0.0036	-0.0068
363	-0.0127	-0.0030	-0.0055
373	-0.0105	-0.0025	-0.0041

Simulation results for the set-point tracking of the HEN are presented in Figures 3, 4. The control responses of the kerosene temperature in the outlet stream reached using the gain-scheduled PID controller and two conventionally tuned PID controllers are shown in Figure 3. The gain-scheduled PID controller ensured the control response with the smallest overshoots. Figure 4 presents the control input - the flow rate of cooling water. The control responses were compared also numerically using the integral quality criteria IAE (integrated absolute error) and ISE (integrated squared error) (Ogunnaike and Ray, 1994). The energy consumption was measured by the total volume of the coolant V_{total} consumed during control and by the heat Q_{total} transferred from the kerosene to the cooling water during control. The numerical results are presented in Table 4. The gain-scheduled PID controller assured the best set-point tracking also according to IAE and ISE. The coolant consumption V_{total} was the smallest when the gain-scheduled PID controller was used, and the operation of the HEN was the best from the economy point of view. The heat transferred to the cooling water Q_{total} was also the smallest when the gain-scheduled PID controller was used, and the goal of control was achieved with the minimum energy.

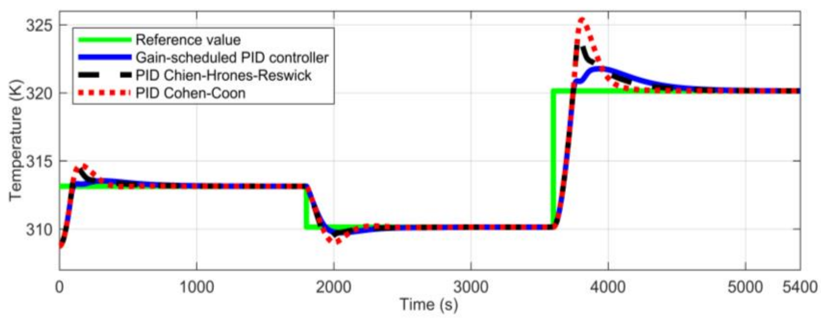

Figure 3: Control responses of the kerosene temperature in set-point tracking

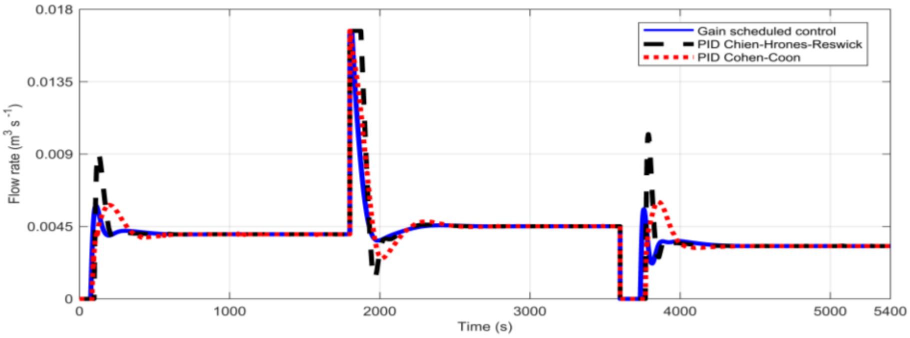

Figure 4: Control input - the flow rate of cooling water in set-point tracking

Table 4: Values of IAE, ISE, V_{total}, and Q_{total} in set-point tracking

PID Controller Tuning Method	IAE	ISE	V_{total} (m^3)	Q_{total} (J)
Gain scheduling	41.26	156.98	21.10	1.18×10^7
Cohen-Coon	43.58	199.02	21.83	1.23×10^7
Chien-Hrones-Reswick	44.43	179.20	22.00	1.24×10^7

The gain scheduled PID controller and two conventional PID controllers were compared also in set-point tracking and disturbance rejection. The disturbances were represented by increasing of the volumetric flow rate of kerosene from 0.0058 m^3s^{-1} to 0.0075 m^3s^{-1} at the time 900 s, then by decreasing of the kerosene flow rate to 0.0062 m^3s^{-1} at the time 2700 s and finally by increasing the kerosene flow rate to 0.0085 m^3s^{-1} at the time 3600 s. Simulation results are shown in Figures 5, 6. The gain-scheduled PID controller ensured the control response with the smallest overshoots. The values of IAE, ISE, V_{total}, and Q_{total} are compared in Table 5. According to these values, the gain-scheduled control ensured the best set-point tracking as well as disturbance rejection, the operation of the HEN was the best from the economy point of view, and the goal of control was achieved with the minimum energy.

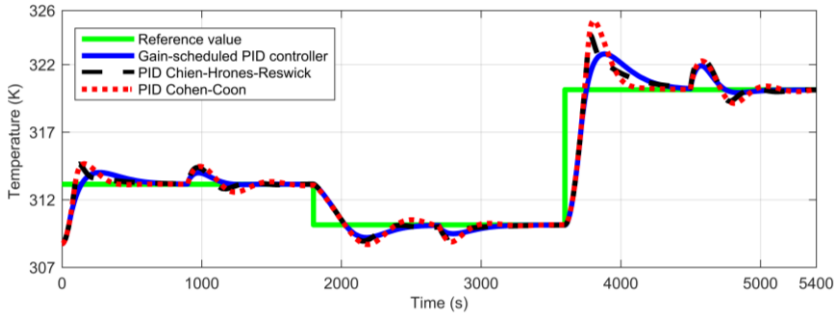

Figure 5: Control responses of the kerosene temperature in set-point tracking and disturbance rejection

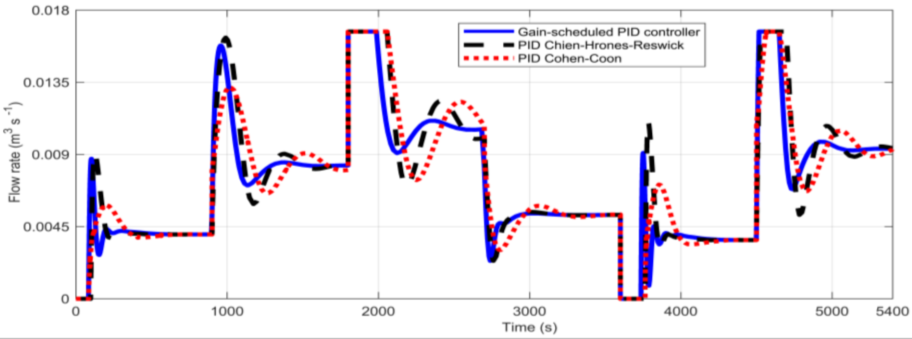

Figure 6: Control input - the flow rate of cooling water in set-point tracking and disturbance rejection

Table 5: Values of IAE, ISE, V_{total}, and Q_{total} in set-point tracking and disturbance rejection

PID Controller Tuning Method	IAE	ISE	V_{total} (m^3)	Q_{total} (J)
Gain scheduling	59.36	179.66	38.95	1.14×10^7
Cohen-Coon	67.66	223.38	40.08	1.19×10^7
Chien-Hrones-Reswick	60.96	197.61	40.49	1.19×10^7

4. Conclusions

This paper is devoted to the design of the gain-scheduled controller for control of five counter-current heat exchangers in series. Simulation results obtained using the gain-scheduled PID controller were compared with the results obtained by two conventional PID controllers. The best control responses with the smallest overshoots and the best values of numerical quality criteria IAE and ISE were reached using the gain-scheduled PID controller. This controller also provided the smallest coolant consumption and the smallest amount of heat transferred to the cooling fluid during the control, thus ensuring the most economical operation and the smallest energy needed to achieve the control goal. The advantage of the GS design is that linear control design methods can be applied to the nonlinear processes. The price for this advantage is that the process has to be linearized at each operating point, and the different controller parameters have to be set according to the operating point. As the linear control techniques are applied, only local stability is ensured. Decisions to be made are system-dependent, including the choice of an appropriate scheduling variable and scheduling procedure. The benefits of the gain-scheduled control are the possibility to use PID controllers in control applications, the tight control of processes with nonlinear behavior, control leading to energy savings and much simpler design compared to advanced control techniques, as e.g. robust MPC or NNPC.

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References

Bakar S.H.A., Hamid M.K.A., Wan Alwi S.R., Manan Z.A., 2017, Sensitivity analysis of industrial heat exchanger network design, Chemical Engineering Transactions, 56, 1489-1494.

Bakošová M., Oravec J., Vasičkaninová A., Mészáros A., 2017, Neural-network-based and robust model-based predictive control of a tubular heat exchanger, Chemical Engineering Transactions, 61, 301-306.

Bojan-Dragos C.A., Precup R.E., Tomescu M.L., Preitl S., Tanasoiu O.M., Hergane S., 2017, Proportional-integral-derivative gain-scheduling control of a magnetic levitation system, International Journal of Computers Communications & Control, 12, 599-611.

Gu S., Liu L., Bai Y., Zhang J., Du J., 2017, Heat exchanger networks synthesis considering dynamic flexibility, Chemical Engineering Transactions, 61, 199-204.

Krhovják A., Talaš S., Rušar L., 2017, 1DOF gain scheduled pH control of CSTR, Proceedings of the 31st European Conference on Modelling and Simulation, Budapest, HU, 391-396.

Nemet A., Klemeš J.J., Moon I., Kravanja Z., 2017, Synthesis of safer heat exchanger networks, Chemical Engineering Transactions, 56, 1885-1890.

de Oliveira V., Karimi A., 2012, Robust and gain-scheduled PID controller design for condensing boilers by linear programming, IFAC Proceedings Volumes, 45, 335-340.

Oravec J., Bakošová M., Meszáros A., 2016, Robust model predictive control of heat exchangers in series, Chemical Engineering Transactions, 52, 253-258.

Rugh W.J., Shamma J.S., 2000, Research on Gain Scheduling, Automatica, 36, 1401-1425.

Shamma J.S., 2012, An overview of LPV systems. In: Mohammadpour J., Scherer C. (Eds.), Control of linear parameter varying systems with applications, Springer, Boston, MA, 3-26.

Sun L., Zha X.L., Luo X.L., 2017, Coordination of bypass control and economic optimization for heat exchanger network with stream splits, Chemical Engineering Transactions, 61, 187-192.

Vasičkaninová A., Bakošová M., 2015, Control of a heat exchanger using neural network predictive controller combined with an auxiliary fuzzy controller, Applied Thermal Engineering, 89, 1046-1053.

Vasičkaninová A., Bakošová M., Oravec J., Mészáros A., 2017, Neural network predictive controller design for counter-current tubular heat exchangers in series, Chemical Engineering Transactions, 61, 121-126.

Veselý V., Ilka A., 2013, Gain-scheduled PID controller design, Journal of Process Control, 23, 1141–1148.

Zhao P., Nagamune R., 2017, Switching LPV controller design under uncertain scheduling parameters, Automatica, 76, 243–250.