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Predictive Functional Control of counter current heat exchangers

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Abstract: A full first principle model of counter current heat exchangers is used as the internal model of a classical PFC controller. With the use of a specific physical "convexity property" of this type of process, a full straightforward first-principle model is used as the internal model of the controller. The whole strategy is implemented in a classical industrial PLC, which controls this nonlinear process with a minimum effort.

Keywords: Predictive functional control, heat exchanger, nonlinear model, linearization, real-time control

1. INTRODUCTION

The heat exchanger is the most widely used technical system in the world. It is encountered extensively in many industries such as power generation, chemical, pharmaceutical, petroleum, food, etc. and its use is permanent in daily life for the climate control of buildings (HVAC).The volume of the process to be controlled can be small, a few liters, or huge, as in nuclear energy (25 m^3).The market is developing fast and many technical solutions are being proposed by and for different types of industries.

Roughly speaking the target, in the simplest case, is to control the temperature of a volume, shifting from cold to hot, or vice versa. It is not so easy since the heat exchanger is a nonlinear process with multiple inputs. The energy consumption should be reduced and this multivariable nonlinear control should be mastered in a tighter and more economical way.

2. PID VERSUS PFC

There is no competition between PID (Proportional plus Integrating plus Derivative) and PFC (Predictive Functional Control) and both methods have their domain of efficiency. The first PFC was operative in 1968 (Richalet et al., 1978). It was the first model based predictive controller. Today it is in use in almost all types of processes, but, here, it is voluntarily limited to "elementary processes": S1SO (Single Input, Single Output) or TITO (Two Inputs, Two Outputs) plants, (it can be extended!) Why restrain the domain of application? The aim is to be able to implement easily this controller instead of classical elementary PID controllers, while using the already installed classical control blocks of industrial PLCs (Programmable Logical Controller).

PFC can achieve what PID cannot achieve and more easily besides. Its wide diffusion is due to this restricted, but still wide domain, where PID used to reign superb. Today PFC is mainly taught in Technical Schools worldwide and, since 1970, it has been implemented in all existing PLC controllers. It has been applied in a very wide open field of applications, with sampling periods ranging from 66 ms (weapon systems) to 1 h (river dam level).

Is there any difficulty in installing PFC? Yes: up to 90% of the time of implementation is devoted to modeling the process: physical, technical and human problems (with perturbation of the process production) are frequent and slow the action down. PFC extends, significantly, the tool box but does not eliminate other control techniques.

3. THE CONVEXITY PROPERTY

It is the fundamental basic property that rules heat exchangers.

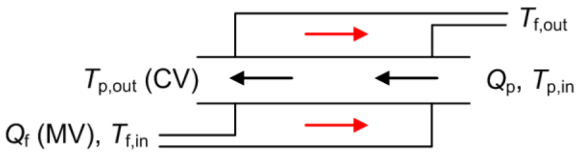

Fig. 1. Counter current heat exchanger

The following notations are used in Fig. 1:

- Q_p: product flow rate
- Q_f: flow rate of heating fluid
- $T_{p,in}$: inlet temperature of product flow
- $T_{p,out}$: outlet temperature of product flow
- $T_{f,in}$: inlet temperature of heating fluid
- $T_{f,out}$: outlet temperature of heating fluid

Let us suppose that there is a hot fluid flow with inlet temperature of $T_{f,in} = 80°$ heating an incoming product counter flow from temperature $T_{p,in} = 20°$. There is no creation of energy, just a passive transfer of some energy from one fluid to the other. The outlet product temperature $T_{p,out}$ becomes a value between 20° and 80°:

$$T_{p,out} = \lambda T_{p,in} + (1-\lambda)T_{f,in}; \qquad 0 \le \lambda \le 1 \tag{1}$$

This type of formulation is known as "convexity" (Abdelghani-Idrissi et al., 2001).

The temperature of both flows (Q_f, Q_p) can be described by the same type of relation: the temperature of the outgoing flows will tend to the temperature of the other incoming flows.

The formal relation (Abdelghani-Idrissi et al., 2001) in (1) is given by (2)

$$\lambda = \frac{1 - e^{-UA\left(\frac{1}{Q_p} - \frac{1}{Q_f}\right)}}{1 - \frac{Q_p}{Q_f} e^{-UA\left(\frac{1}{Q_p} - \frac{1}{Q_f}\right)}} \qquad (2)$$

λ depends on both flows and on UA, which is the product of surface of exchange and the heat exchange coefficient:

$$UA = U \cdot A \qquad (3)$$

- U: heat exchange coefficient
- A: surface of exchange

The surface A is supposed to be known. The heat exchanger coefficient could be more complex depending on the Nusselt parameter (Changenet et al., 2008). UA can be calculated by inversing the basic formula (2) in each sampling time of the control as flow rates, temperatures and λ are known:

$$UA = -\frac{\ln\left(\frac{1-\lambda}{1-\lambda\frac{Q_p}{Q_f}}\right)}{\frac{1}{Q_p} - \frac{1}{Q_f}}$$

- Fig. 3 should be corrected with the actual names of the variables.
- In Figs. 8/a to 8/c and 9/a to 9/c the axis texts should be enlarged and the curves should be named.

(4)

It is to be noted that λ plays the role of a "functional intermediate manipulated variable", coming from the PFC controller and acting by an equivalent process, while the flows Q_f and Q_p are the possible "physical manipulated variables".

4. CALCULATION OF THE MANIPULATED VARIABLE

The control aim is to keep the outlet temperature of the product constant. That means

$$T_{p,out,SP} = T_{p,out} = \lambda T_{p,in} + (1-\lambda) T_{f,in} \qquad (5)$$

where

- $T_{p,out,SP}$: set-value of outlet temperature of product flow.

From (5) we see that functional intermediate manipulated variable λ is a linear function of the measured temperatures and the desired product outlet temperature

$$\lambda = \frac{T_{f,in} - T_{p,out,SP}}{T_{f,in} - T_{p,in}} \qquad (6)$$

The physical manipulated variable has to be calculated from the functional intermediate manipulated variable.

Three different control strategies exist, seeFig. 2.

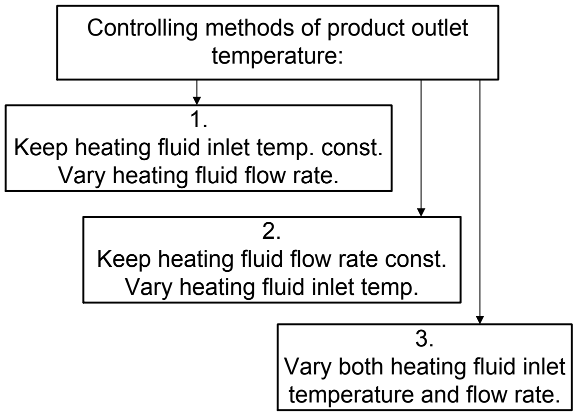

Fig. 2. Three possible control algorithms

Two of the control algorithms are explained in detail.

1. Manipulating of fluid flow

The inlet temperature is kept constant by manipulating the heater power and using e.g. a PFC controller. The functional intermediate manipulated variable λ is the output of another PFC controller. The physical manipulated variable is the fluid flow (Q_f) which can be calculated from (2). There is no analytical solution of the inverse equation if (2). The numerical solution has to be reliable in a large domain of action, and easy to implement in an ordinary industrial PLC. The primitive elementary approach is to scan the whole domain of Q_f and to select the condition where the calculated $\lambda(Q_f)$ by (2) is equal to the λ required by the controller
It is to be noted that UA is computed at every sampling period on-line from the actual values of both flows Qf and Qp and past value of λ. UA varies with the environment in an complex way, but it does not vary much between two sampling times, then it is possible to update its value with a classical robust iterative procedure (see Fig. 3) and thus compute the new action Qf.

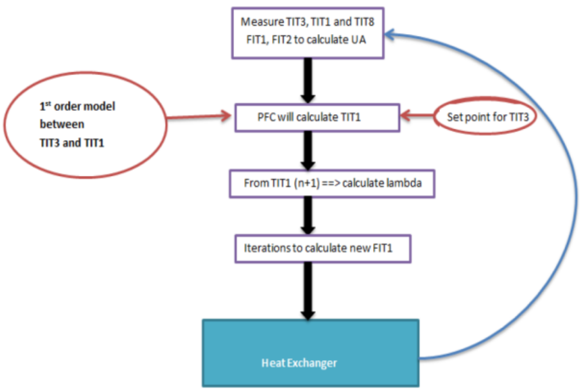

Fig. 3. Iterative on-line computation of UA in real time

The process model is known, and its transfer function can be identified in most cases as a first-order process with a dead time. Then we are in front of a classical PFC control and the selection of its desired CLTR (Closed Loop Time Response) solves the problem. The implementation in any PLC is straightforward.

2. Manipulating of fluid inlet temperature only

   The fluid flow is kept constant by e.g. a basic controller and the inlet temperature of the fluid is manipulated by using a PFC controller. As it is seen form (1) and (5) the product outlet temperature depends linearly on the heating fluid inlet temperature.

Heat exchangers have nonlinear dynamics : gain and time delay depend on the flow values, but PFC takes into account all these features.

5. CASE STUDY

5.1 Pilot plant

The pilot plant is seen in Fig. 4 with the product flow (blue) and heating fluid flow (red) marked. The heat exchanger E-1 has to heat the inlet temperature of the flow to the reactor.

5.2 Experimental modeling

First-order linear models have been fitted between the heating power and the heating fluid inlet temperature from step responses with different heating fluid flow values between 200 and 800 LPH (liter per hour). The results of the parameter estimation are summarized in Table 1.

Table 1. Estimated model parameters

Heating fluid flow [LPH]	Static gain	Time constant [s]	Dead time [s]
200	0.220	35	37
300	0.145	35	35
400	0.096	35	30
500	0.090	35	24
600	0.085	35	20
700	0.078	35	16
800	0.058	35	12

As it is seen, the time constant was constant and both the static gain and the dead time decreased with increasing flow value. Figs. 5/a and 5/b show the dependence of the static gain and the dead time on the flow. The following symbols were used

- K_P: static gain
- T_d: dead time
- T_1: time constant (not plotted, as constant)

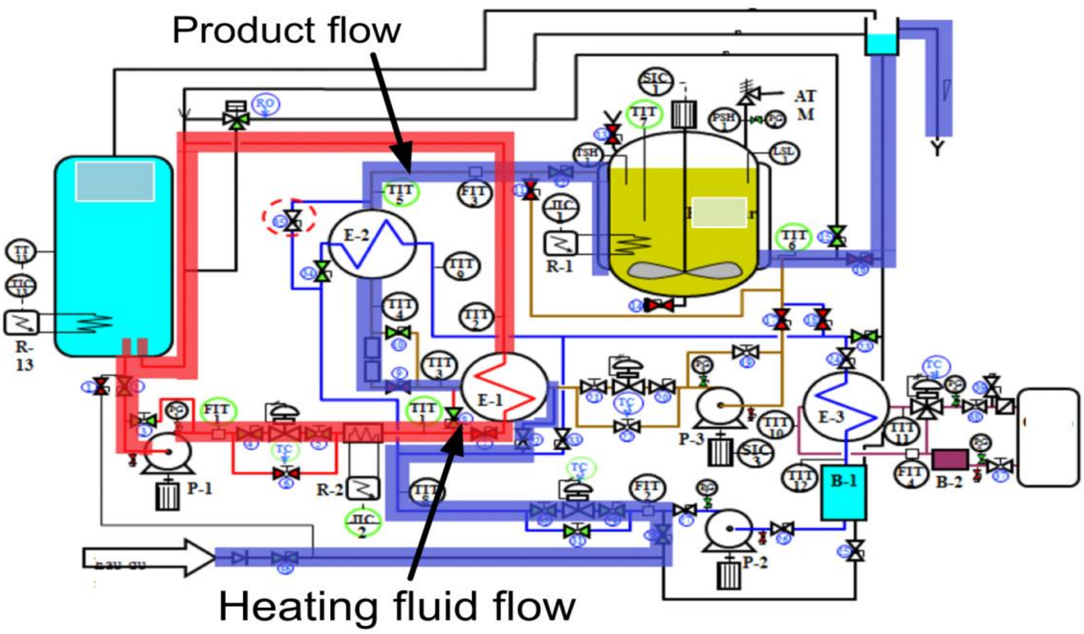

Fig. 4. Pilot plant with product and heating flows marked

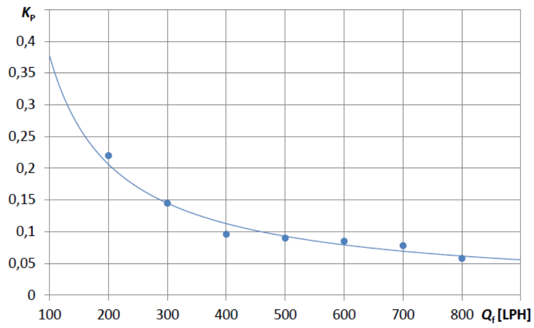

Fig. 5/a. Estimated static gain versus heating fluid flow

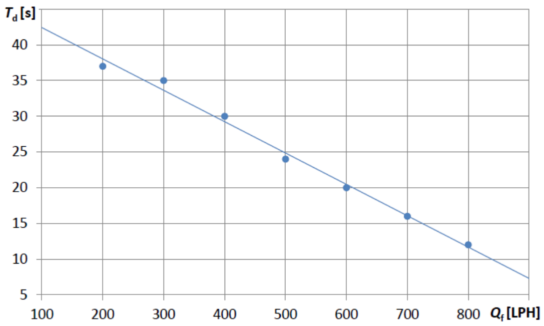

Fig. 5/b. Estimated dead time versus heating fluid flow

The three estimated model parameters depend on the heating fluid flow with rough approximation as given below ("^" means estimated value):

$$\hat{K}_p = \frac{44}{Q_f}$$

$$\hat{T}_d[\mathrm{s}] = 50 - \frac{Q_f[\mathrm{LPH}]}{20}$$

$$\hat{T}_1[\mathrm{s}] = 35$$

A model was also identified between the heating fluid flow and the product outlet temperature(Fig. 6)shows both the measured product outlet temperature and the estimated calculated model outputs, $T_{p,out}$ and $\hat{T}_{p,out}$, respectively, for approximate stepwise changes of the heating fluid flow.

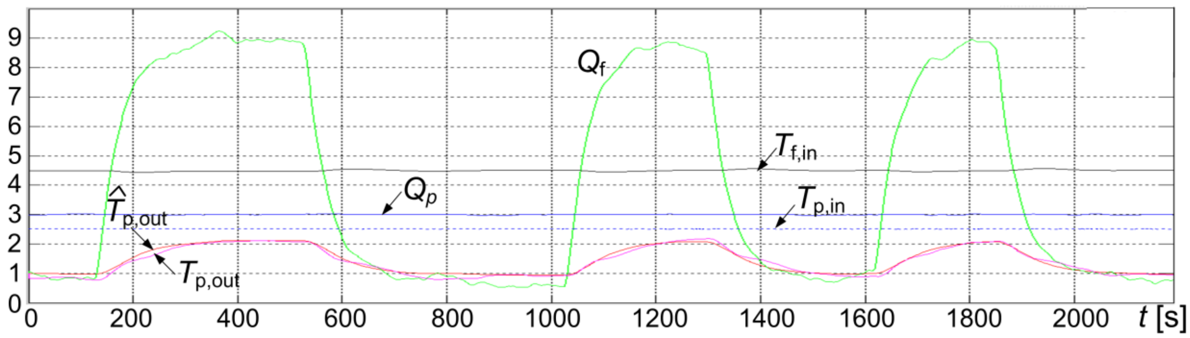

Fig. 6. Measured product outlet temperature and the estimated model calculated model output

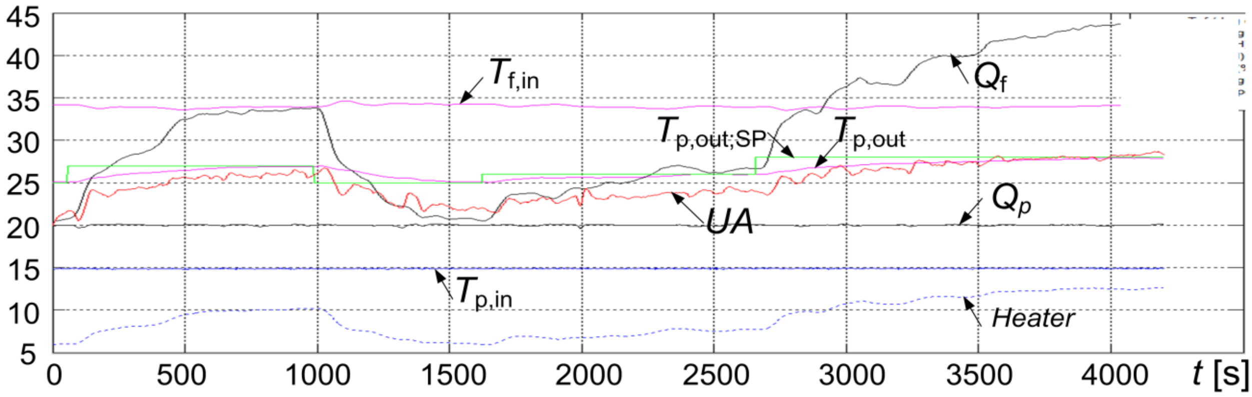

Fig. 7. Control of the product outlet temperature by manipulating the heating fluid flow

5.3 Real-time control implementation

The product outlet temperature was controlled by the two methods presented in Section 4.

Method 1:

The product outlet temperature was controlled by manipulating the heating fluid flow while keeping the inlet temperature of the heating flow constant. The process model of the heating loop was identified in Section 5.2 and the corresponding PFC controller manipulates the heater power and uses this identified nonlinear model.

As it is seen from Fig 7, the controlled signal follows the fast and aperiodical set-value. (The set-value was stepwise changed between t=50s, t=1600s and t= 2650 s.) It is also seen, that the product of the surface of exchange and the heat exchange coefficient (UA) were calculated in real-time.

Method 2:

There is a special local problem in this unit since the fluid goes from the heat exchanger to a source tank that feeds back this fluid to the process. Thus the process tends to be almost integrative! But there are natural heat losses in the connecting pipes. Fig. 8/a to 8/b show the measured product outlet temperature and its identified model, for different heating flows.

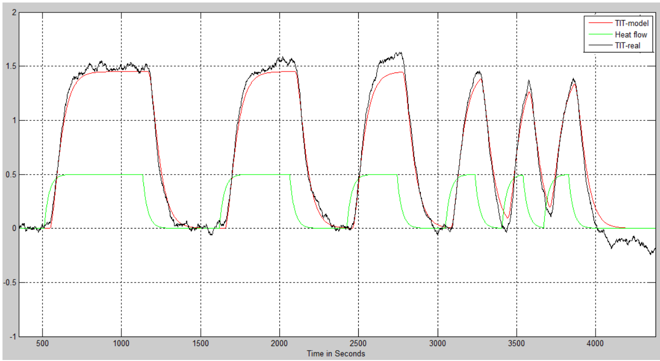

Fig. 8/a. Measured product outlet temperature, and its identified model at heating flow of 300 LPH

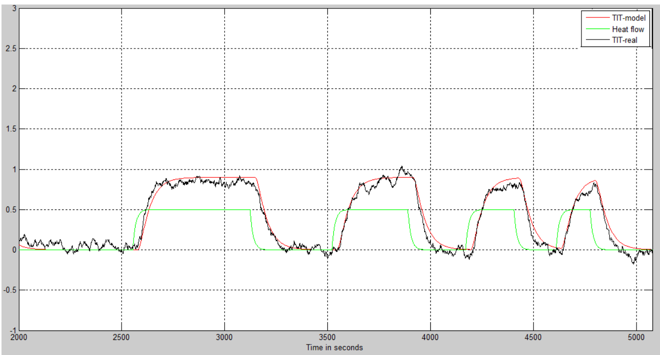

Fig. 8/b. Measured product outlet temperature, and its identified model at heating flow of 500 LPH

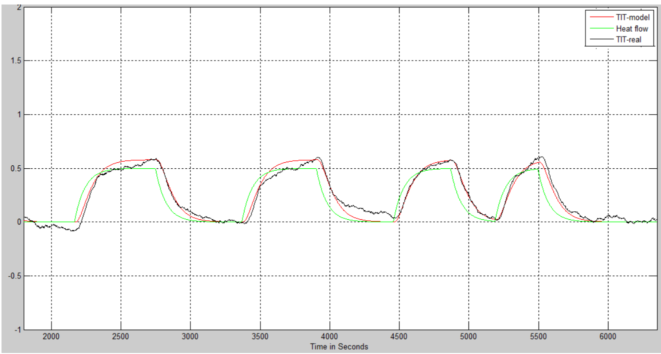

Fig. 8/c. Measured product outlet temperature, and its identified model at heating flow of 800 LPH

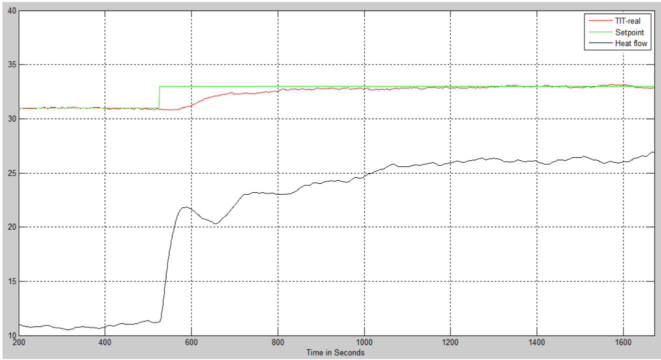

Fig 9/a. Control of the product outlet temperature by manipulating heating power at heating flow of 300 LPH

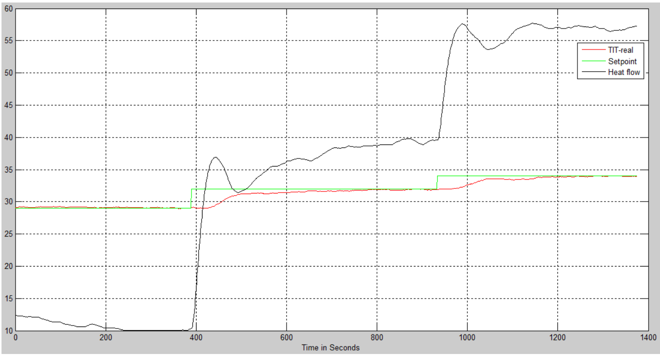

Fig. 9/b. Control of the product outlet temperature by manipulating heating power flow of 500 LPH

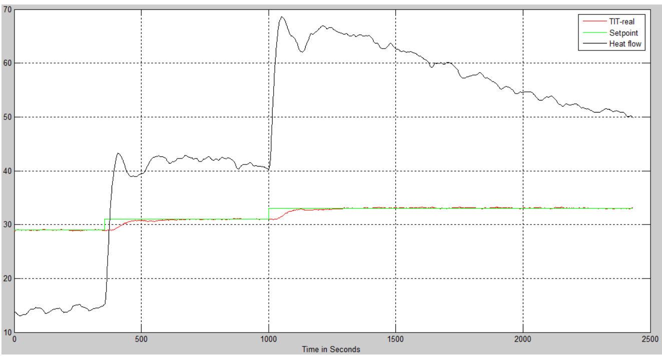

Fig. 9/c. Control of the product outlet temperature by manipulating the heating power flow of 800 LPH

6. CONCLUSION

A heat exchanger is a nonlinear process as the parameters depend on the flow values. The relation between heating flow as a manipulated variable and the product outlet temperature as a controlled variable is nonlinear as well. The paper shows how the control can be linearized considering the convexity theorem and a "functional intermediate manipulated variable" beside the "physical manipulated variable". As announced, the process depends on different variables, but since they are all measured on-line, this self-adaptability confers to this procedure a noticeable efficiency: the local environment is permanently measured, and the nonlinear, non-stationary nature of the process is taken into account. Two different control algorithms are presented, depending on the choice of the physical manipulated variable. Off-line process identification and real-time temperature control were realized successfully and were presented. Using the physical model and PFC controller led to better results than black-box modelling and PI(D) control. Several industrial applications attest the benefit and convenience of the methods presented.

A simultaneous action with flow and temperature could be an interesting research topic !

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