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Research Paper

Practical validation of the effective control of liquid–liquid heat exchangers by distributed parameter balance-based adaptive controller

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HIGHLIGHTS

- Model-based advanced controller for the liquid-liquid heat exchangers is suggested.
- Implementation in Programmable Logic Controller is discussed.
- Suggested controller is validated by experimental results.
- In comparison to the conventional control approach, it shows its superiority.

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ABSTRACT

This paper presents the concept of model-based control of water-water heat exchangers. Based on the simplified distributed parameter model of the unit, the distributed parameter Balance-Based Adaptive Controller is suggested and its properties are discussed. Then, the practical issues are presented for the industrial applications in the Programmable Logic Controllers. Final practical experimental stage is based on the laboratory heat exchange and distribution system and the results show that the suggested concept outperforms the control system based on the conventional PID controller, especially in terms of the disturbances rejection.

1. Introduction

Recently, more and more advanced design methods and control strategies for Heat Exchanger Networks (HENs), operating as a part of many industrial processes, have been developed to reduce energy consumption and ensure high safety and environmental goals [1–5]. Apart from high-level optimal control of HEN's operating in industry, the effective low-level control of heat exchangers is also an important issue and for this purpose, different advanced control techniques have been recently reported. Bakošová and Oravec [6] suggested robust approach to model predictive control of heat exchangers. The example application of Predictive Functional Controller (PFC) to heat exchanger regulation can be found in [7]. At the same time, Laszczyk et al. [8] presented comparison of control performance between Dynamic Matrix Controller (DMC) and PFC in the application to heating process. Vasičkaninová et al. [9] report application of hybrid approach based on neural network mixed with predictive control. Maidi et al. presented two interesting applications of linearizing control based on first principle distributed parameter modeling for counter flow [10] and parallel flow [11] configuration. They discussed stability issues but validation was carried out only by simulation. In [12], authors introduce fuzzy controllers and compare them with conventional PI(D) controllers in the application to plate heat exchanger. In both cases, tuning is based on first principle model. Practical validation of two nonlinear control techniques (namely, Process-Model Based Control and Generic Model Control) based on simplified first principle modeling and applied for pilot scale heat exchanger is reported by Raul et al. [13]. Michel and Kugi [14] suggest model-based approach, in which they redefine the conventional control goal. Instead of outlet temperature, the total thermal energy stored in both heat exchanger chambers is defined as controlled variable.

This paper deals with the concept of the synthesis of the heat exchanger (HE) advanced controller that comes from the Balance-Based Adaptive Control (B-BAC) methodology [15]

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Nomenclature

F	flow rate [m^3/s]
F_{SP}	set-point for flow controller
$f(.)$	function component of the general simplified model
$g(.)$	function component of the general simplified model
h	substitute model parameter representing heat exchange [1/s]
i	time discretization index
$\hat{L}_j(z)$	Lagrange polynomial component
$N+1$	number of space discretization points
p	substitute model parameter representing flow conditions [1/m^3]
P	parameter of the estimation procedure
P_h	percentage of heater power supply range [%]
P_{nom}	nominal power of heater [W]
R_Y	additive modeling uncertainty
$\hat{R}_Y$	on-line estimate of the additive modeling uncertainty
t	time [s]
T	fluid temperature [°C]
$\hat{T}$	estimated fluid temperature [°C]
T_{in}	heat exchanger inlet temperature [°C]
T_{hin}	inlet temperature for the electric flow heater[°C]
T_{out}	heat exchanger outlet temperature [°C]
T_{hout}	outlet temperature from the electric flow heater [°C]
T_s	sampling time [s]
u	manipulating variable
Y	controlled variable
Y_{sp}	set point value
z	normalized space variable [–]

Chosen abbreviations

AHS	adjustable heat source
B-BAC	balance-based adaptive controller
dpB-BAC	distributed parameter balance-based adaptive controller
EFH	electric flow heater
HE	heat exchanger
HEN	heat exchange network
OCM	orthogonal collocation method
PHE	plate heat exchanger
PI(D)	proportional integral (derivative) controller
WRLS	weighted recursive least squares method

Greek symbols

α	tuning parameter for B-BAC controller (forgetting factor for WRLS) [–]
λ	tuning parameter for B-BAC controller [1/s]

Subscripts

1	hot fluid
2	cold fluid
p	primary control loop
s	secondary control loop

dedicated to control nonlinear SISO (Single Input Single Output) industrial processes. Its successful experimental validation for the control of heat exchange and distribution systems can be found in [16–18]. More details on its theoretical background, stability and other properties are discussed in [18]. This concept was also extended for distributed parameter heat exchange systems [20,21] but validated only by simulation. In this paper, this concept is further developed to the distributed parameter B-BAC (dpB-BAC) that benefits from B-BAC methodology but it is based on the simplified distributed parameter model of HE.

Apart from theoretical background and justification for dpB-BAControl methodology, the very important highlight of this paper is reporting the stage of practical implementation and validation of the suggested model-based technique. A huge number of different advanced control techniques for low-level process control have been proposed in literature for last decades but only for few of them, the practical aspects of PLC-based implementation and of at least laboratory validation were considered. This paper completes this missing part for suggested dpB-BAC methodology and provides the pieces of information that are important for practitioners who want to apply it in the industrial practice for effective control of HE's.

2. Problem statement

Let us consider the problem of deriving the model-based controller for water-water counter-flow HE operating in the setup presented in Fig. 1. The primary circuit for hot water is supplied by the heat source (AHS) with adjustable desired temperature T_{in1} at the HE inlet, which is considered as the manipulating variable for HE controller. The secondary circuit for cold water represents heat demand. It is assumed that in both circuits, the flow rates F_1, F_2 [m^3/s] and the temperatures T_{in1}, T_{in2}, T_{out1}, T_{out2} [°C] are measured on-line at the sampling time T_s [s]. The desired temperature T_{in1}

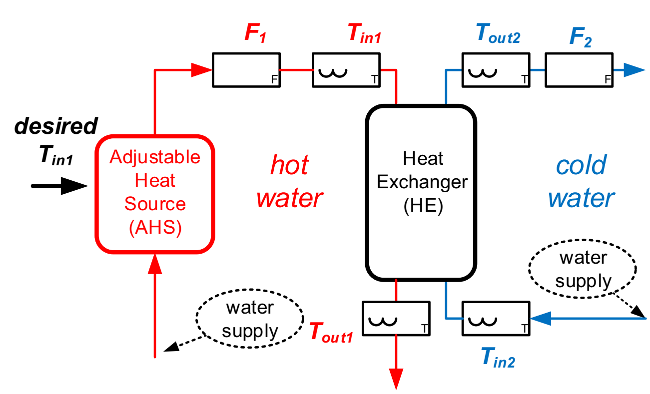

Fig. 1. Example application setup for heat exchanger.

must be adjusted by the designed HE controller. Consequently, the control goal is defined to stabilize the outlet temperature $Y = T_{out2}$ at the desired set point Y_{sp} by manipulating the inlet temperature $u = T_{in1}$ supplied by AHS. This approach is acceptable only in small HENs with adjustable AHS but it provides more energy-efficient control comparing to the case when the manipulating variable is the flow rate F_1. The system is disturbed by variations of heat demand (namely, of Y_{sp} and of F_2) and by potential variations of T_{in2} and of F_1. The designed controller should:

- provide significant improvement in control performance, comparing to the conventional PI(D) control system,
- ensure robustness to process uncertainties, especially on liquids rheology,
- provide relatively low computational complexity to allows for practical implementation in industrial PLC (Programmable Logic Controllers).