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Counter-current tubular heat exchanger: Modeling and adaptive predictive functional control

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Abstract

The control of the outlet temperature of a counter-current tubular heat exchanger in heater configuration with the predictive functional control is presented in this paper. The outlet temperature of the cold fluid is controlled by variation of the flow of the hot fluid while the inlet temperatures corresponding to the principal inputs are maintained constant. An approximated first order model, corresponding to the response of the heat exchanger to a step change of the flow rate is used to apply the functional predictive control. The gain and the time-constant of this model depend on the initial and final steady state temperatures according to the flow rates. This nonlinear dynamic model, obtained from the partial differential equations (PDE) is taken into account to apply the functional predictive control, which was validated experimentally in various configurations. The robustness of this controller is also examined when the system is subjected to the sudden change of the flow rate of the cold fluid.

Keywords: Tubular heat exchange; Heater; Temperature control; Model-based predictive control

1. Introduction

In much of industrial thermal applications, the heat exchanger constitutes important equipment for the control of the temperatures and the heat exchange. This thermal system is generally controlled by the flow rate corresponding to a parameter and not by the inlet temperatures corresponding to the principal inputs of this one. The nonlinear effects must consequently be taken into account to control this kind of system. A simple controller of type PI (Proportional-Integral), tuned by hand, is frequently adequate to control the outlet temperature. But if the tubes are rather long, the tubular counter-current heat exchanger presents an important lag time corresponding to the residence time when the inlet temperature changes. In this case, controllers PID (Proportional-Integral-Derivative) lose their effectiveness. The parameters of the model involving the various temperatures change with the flow rates of the fluids and the adjustment of the controller should change with the fluids flow rates, which could be a tiresome work. Model-based Predictive Control MPC gives an alternative for the effective control of the nonlinear processes such as the thermal equipment. In the case of the heat exchanger, if the model of the controller is obtained from the first principles and if its parameters are renewed in real time by real measurements of the flow rates and the temperatures, a permanent natural adaptation of the controller with the environment is feasible. It should be noted that a black box model type, where the parameters do not have any physical significance, could not be used because of the strong nonlinearities. Simplified models based on enthalpy and mass balances are used, insofar as they were identified by real data in order to have a good predictability. Based on a set of physical equations with a clear physical

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Nomenclature

a	wall thickness [m]
A	heat transfer area [m^2]
Bi	Biot number
C_p	specific heat [J kg^{-1} K^{-1}]
D	diameter [m]
h	heat transfer coefficient [W m^{-2} K^{-1}]
H	horizon [s]
J	quadratic criterion
K	coupling coefficient [s^{-1}]
L	heat exchanger length [m]
Q	mass flow rate [kg s^{-1}]
t	time [s]
T	temperature [K]
V	mean velocity [m s^{-1}]
Vol	volume [m^3]
x	axial position [m]

Greek symbols

β	dimensionless parameter
ε	error
ϕ	flux [W]
λ	thermal conductivity [W m^{-1} K^{-1}]
μ	parameter
ρ	density [kg m^{-3}]
τ	time constant [s]
χ	parameter

Subscripts

B	base
c	cold fluid
e	outer tube
h	hot fluid
i	inner tube
in	input stream
m	model
out	output stream
p	process
r	reference
set	set point
w	separating wall

Superscripts

0	Initial conditions
∞	final conditions

significance, they can be used for on-line adaptation. In this case, MPC allows the explicit integration of phenomenological process models in the system control.

Moreover, this kind of systems is governed by the partial derivative equations (PDE) when a local modeling is employed [1,2]. A model obtained by first order approximation describing the response of the temperature along the heat exchanger to a step change of flow rate is proposed in Refs. [3–5]. This model is derived from the system of PDE describing the transport and the transfer of heat by convection. This dynamic model can be employed to apply the control of this system. The good control effectiveness of these systems makes necessary the use of the advanced control techniques based on dynamic internal models. Many researchers have shown the feasibility of the predictive control in the industrial applications. Richalet et al. [6] have published the first paper on the IDCOM and the application to the petrochemical area. The first comprehensive exposition of generalized predictive control (GPC) was presented by Clarke et al. [7,8]. Predictive control of chemical reactors has been the subject of several studies [9–12]. In Ref. [13], a model-based predictive controller was coupled to particle swarm optimisation algorithm to control a greenhouse air temperature. Richalet [14,15] also developed the predictive functional control (PFC), which will be used and presented in this paper. Morari and Lee [16] gave an overview of the origins of model predictive control and its popularity. The robustness of the model predictive control was investigated and applied to the temperature control of an open-loop unstable continuous stirred tank reactor [17]. The present paper deals with the predictive functional control applied to a counter-current heat exchanger. The PFC is based on an internal adaptive model corresponding to the response to flow rate used in the algorithm command. The principle of predictive functional control is also recalled.

2. Description and modeling

The system studied in this work corresponds to a water/water counter-current tubular heat exchanger as described on Fig. 1. The inner pipe is a copper tube and the outer one is a stainless steel tube. The hot fluid crosses the circular duct and the cold fluid circulates in the annular duct. The thermocouple probes are placed at the inlet and the outlet opposite sides of the tubular heat exchanger. The flow rates of the two fluids are controlled using two valves. The probes and the valves are connected to a data acquisition system in order to monitor the data and to adjust the two fluids flow rates. In this paper, the heat exchanger is used in a heater configuration. The controlled variable is the cold fluid outlet temperature and the manipulated variable is the hot fluid flow rate. The geometrical and physical parameters of the heat exchanger are reported in Table 1.

Patankar et al. [18] proposed the mathematical model used in this study. The assumptions made in our case are:

- Fluids are in turbulent flow.
- Heat conduction along the flow axis is neglected.
- Fluids are incompressible and single phased.