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Dynamic modeling and control of plate heat exchanger

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ABSTRACT

A general model has been developed to suggest the transient responses of a plate heat exchanger. The predicted and experimental step responses of the system have been analyzed using the frequency response analysis. The results indicate that the system is represented by a first order lag and dead time. A closed fit between the simulated and experimental data has been obtained.

To verify the presented model, temperature control has been applied on the plate heat exchanger using both conventional and fuzzy logic controllers. Results show that the performance of the fuzzy logic controller produces transient responses with less settling time and less oscillatory behavior compared to that under the conventional controller. Comparisons between simulated and experimental responses indicate that the developed model is capable of predicting the transient responses of the plate heat exchanger, satisfactory.

1. Introduction

Plate heat exchangers are important components of chemical processes and power industries; they are being increasingly used in petrochemical processes due to their highly efficient heat recovery and their compactness [1]. Plate heat exchangers are probably the most common type of heat exchangers applicable for a wide range of operating temperatures and pressures. Aminian et al. [2] stated that plate heat exchanger weighs 95% less than comparable conventional shell-and-tube exchangers and provide 1000–1500 square meters of heat transfer per cubic meters of exchanger volume.

Due to the importance of the plate heat exchangers, many researchers have investigated the modeling and the optimum design parameters for the system. For example; Lalot et al. [3] have suggested a non-linear model using an extended Kalman filter and it has been applied to on-line detection of fouling in the heat exchanger. Ling and Peng [4] have developed artificial neural networks in order to predict the pressure drop and heat transfer characteristics in the plate heat exchanger. Mishra et al. [5] have used a generic technique of algorithm-based optimization for plate heat exchangers. Their optimization program is aimed to minimize the number of entropy generations for a specific heat duty. Yang et al. [6] have developed a 3-dimensionally distributed-parameter model for plate heat exchangers. The model allows for varying the local fluid thermo-dynamical properties inside the flow path.

It is very important to know the behavior of plate heat exchangers when they are subjected to transient flow and to know the flow variation required to control them when temperature changes take place. Dynamic analysis of plate heat exchangers provide information about transient responses subjected to various disturbances. However, there is a limited number of studies that have been reported on the transient analysis and control of plate heat exchangers. Burns [7] has developed a model for a heat exchanger system based on the analysis of the real poles and zeros of the system transfer function. His results indicate that the transfer function of the heat exchanger can be approximated by a lead/lag function. Ghanim [8] has studied the dynamics of plate heat exchangers using a step change technique applied to the cold water flow rate. His analysis of the results shows that the system is represented by a first order system with a negligible time delay. In his work, the time constant has been measured for various flow rates and he concluded that the time constant is inversely proportional to the flow rate. Also, another theoretical and experimental analysis of the dynamic characteristics of plate heat exchangers has been presented by Khan et al. [9]. Their investigation has shown that the system is modeled by first and second order transfer function with dead time. Recently, Das and Dwivedi [10] have used a predictive model to suggest transient responses for different variable changes, however, no clear model or transfer function has been presented. Mahdi et al. [11] have developed a two-dimensional dynamic model for milk fouling in a plate heat exchanger. Their conclusion stated that the aggregation rate of unfolded protein is found to increase exponentially with wall temperatures rising and can be accompanied by a substantial reduction in the heat-

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Nomenclature

a	constant in Eq. (8)
A	area of heat transfer, m^2
b	constant in Eq. (8)
c	constant in Eq. (8)
Cp	specific heat, J/kg K
D	derivative control
e	error, K
I	integral control
G	transfer function
$\dot{m}$	mass flow rate, kg/s
$i\omega$	imaginary
K	gain, K/kg/s
M	mass capacity, kg
P	proportional control
$P(t)$	controller output pressure signal, psi
S	Laplace term
t	time, s
T	Temperature, K
U	over all heat transfer coefficient, W/m^2 K

Subscript

C	cold water & controller
D	derivation
H	hot water
I	inlet
I	integral
o	outlet
P	process
ss	steady-state

Greek

ζ	damping coefficient
τ	time constant
ω	frequency

Abbreviation and nomenclature on the schematic diagram

ADC	analog to digital converter
A_{mp}	volt amplifier
AP	air-compressor
APR	air-pressure filter and regulator
DAC	digital to analog converter
FCV	flow control valve
I/P	current to pressure converter
P_1	cold water pump
P_2	hot water pump
PC	personal computer
PHE	plate heat exchanger
R_1	hot water rotameter
R_2	cold water rotameter
T100	cold water tank
T200	hot water tank
TE	temperature element
TIC	temperature indicator control
TT	temperature transmitter
V/I	volt to current converter

transfer coefficient. Tan et al. [12] have studied the use of artificial neural networks in order to simulate the thermal performance of a plate heat exchanger with no suggested model or transfer function.

Only a few researchers have focused on the control of heat transfer systems such as boiler and plate heat exchangers. Assilian and Mamdani [13] have realized that the fuzzy logic controller could be used not only in the treatment of complex heuristic systems, but it could also be applied to hard systems such as industrial plant controllers. In their report, small boiler steam engine controllers specifying heuristic fuzzy control rules for two feedback loops have been implemented and the results have been compared with those of the Direct Digital Control for different set points. The results show that the quality of control with the fuzzy controller is better than that obtained by the fixed controller. Kickert and Van Naute Lemke [14] have applied three types of fuzzy logic controllers to the temperature control of a warm water plant and compared the results with that under the conventional PI controller. They used a continuous type membership functions to describe the fuzzy sets. The process has properties that are difficult to control. These difficulties arise from non symmetric behavior for heating and cooling, noise, dead time and the influence of the ambient temperature on behavior of the process. King and Mamdani [15] have applied a temperature control using a fuzzy logic controller on the boiler and stirred tank reactor. The formulating design rules of the fuzzy logic controller require some knowledge of the process such as process delays, and speed and magnitude of responses. They concluded that processes could be controlled effectively using heuristic rules based on fuzzy statements and the results indicate that the fuzzy control system is much less sensitive to process parameter changes and can give good control at all operating points. Morison [16] has proposed and tested a control algorithm that calculates the set point of the hot water temperature from the set point of pasteurization temperature and an average temperature based on the steady-state analysis and the effects of disturbances on the process temperatures. His results indicate that the control based on a steady temperature is more effective and could be very good for disturbance rejection and set point tracking.

It can be seen that the necessity for developing a general mathematical model for plate heat exchangers is an important task for the purpose of their control and their transient behavior. Thus, the present work has been conducted to find a general dynamic model and a suitable control system for the plate heat exchanger in order to enhance the research studies of the transient dynamics of such systems. Theoretical and experimental works will be carried out; transient responses of the plate heat exchanger will be investigated using frequency response analysis. In addition, one of the goals is to maintain the outlet temperature of the cooling water in the plate heat exchanger using conventional and advanced control systems. The control systems applied are: PI, PID and fuzzy logic controllers. The final results of the performance will be compared theoretically and experimentally.

2. Mathematical model formulation

2.1. Mathematical model of plate heat exchanger

Unsteady-state energy balances have been used as the basis for the derivation of the mathematical model for the plate heat exchanger. Two approaches are possible to employ overall balances. In first approach, the overall heat transfer coefficient (U) is considered to be constant and in the second approach, the overall heat transfer coefficient is considered as a function of the hot stream mass flow rate. Hence, in the latter instance, U is also considered as a function of time (i.e. $U(t)$).

Assuming U to be constant, the unsteady-state energy balance around the cold plate is given by: