CHEMICAL ENGINEERING TRANSACTIONS Volume 18, 2009
Editor Jiří Klemeš
 ISBN 978-88-95608-04-4 ISSN 1974-9791
DOI: 10.3303/CET0918135

Control of Plate Heat Exchanger Outlet Temperature Using Butterfly Valve and Parametric Model Predictive Control Technique

P. Kapustenko*[a], O. Dobromyslova[b], O. Dobromyslov[b], O. Perevertaylenko[b], O. Arsenyeva[a], O. Ilyunin[b], E.Shabanov[b]
[a]National Technical University "Kharkiv Polytechnic Institute", 21 Frunze Str., 61002, Kharkiv, Ukraine
[b]AO SODRUGESTVO-T, 21 Frunze Str., 61002, Kharkiv, Ukraine
kap@kpi.kharkov.ua

In this work the technique to improve flow control quality of butterfly valve with the use of parametric model predictive control was developed. It is implemented through microcontroller with microchip as valve position reading device and was tested on pilot unit in industrial application. For mathematical modeling of butterfly valves the flow characteristics data supplied by its producers were used. For modeling of plate heat exchanger behavior the simplified models are developed. More rigorous, but complex, requiring the use of specialized software and computing time consuming models, available in literature, also can be used in case of specific requirements for accuracy of temperature control. The pilot unit of developed butterfly valve regulator was fabricated and tested on one of district heating substations, which was installed for tap hot water heating in Kharkiv, Ukraine. The comparison of resulted outlet temperature readings, which were obtained with and without parametric model predictive control technique, demonstrated the significant improvement in accuracy of temperature control.

1. Introduction

To maintain the temperature of stream heated or cooled in a heat exchanger at given preset value with limited deviations is one of the most frequently encountered control problems in industry. For this purpose the flow rate regulators are usually used, which control the flow of steam, heating or cooling water at the rate that ensure the specified temperature value of heated or cooled stream at the exit of heat exchanger. Such regulator consists of a control valve with mounted on it actuator and valve control device which governs the valve position according to signal data from temperature sensor. Types of valves are categorized according to their design style. The main of these types, which can be used for flow control are globe, angle, ball, plug, needle and butterfly valves, see e.g. Waite and Eng (2008). The most effective for regulation are globe or saddle regulative valves. Its construction provides linear characteristic of fluid flow passing in the range from open state to close one. This valve type production is

Please cite this article as: Kapustenko P., Dobromyslova O., Dobromyslov O., Perevertaylenko O., Arsenyeva O., Ilyunin O. and Shabanov E., (2009), Control of plate heat exchanger outlet temperature using butterfly valve and parametric model predictive control technique, Chemical Engineering Transactions, 18, 827-832 DOI: 10.3303/CET0918135

made on the high precision costly equipment. As a result the price is high and it increases with the increase of valve passage diameter.
The butterfly valve is one of the most common and its chief advantage is high capacity in a small package and very low cost comparing to saddle valves. There is a considerable drawback in such type of valve when used for automatic flow control, resulting from its design. The dynamic flow characteristic nonlinearity of such valve directly influences the controlling quality. In this work the technique to improve flow control quality of butterfly valve with the use of parametric model predictive control (see Sakizlis et al. (2004)) and microcontroller device and microchip as valve position sensor was developed and implemented on pilot unit in industrial application.

2. Mathematical modeling of plate heat exchanger with outlet temperature control by butterfly valve

2.1 Mathematical modeling of butterfly valve flow characteristic

Most producers of butterfly valves present the flow characteristic data of their valves in technical manuals. The typical flow characteristic curves and coefficient Kv(m^3/h) values versus paddle rotation angle for butterfly valves of different diameters (temperature is 20°C, pressure 1 bar) are presented on Figure 1.

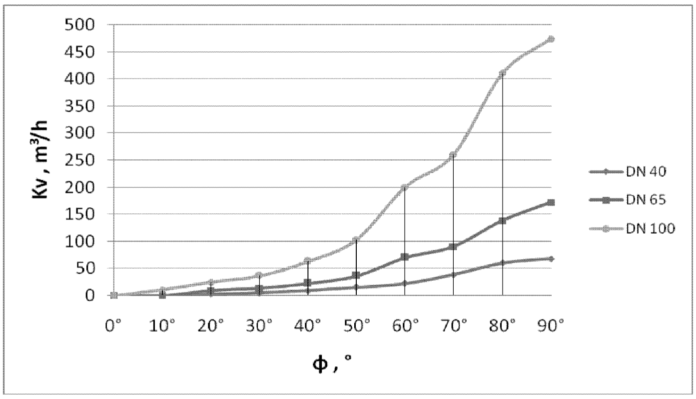


Figure 1. Flow characteristic data for butterfly valves of different diameters

Table 1. Approximation of butterfly valves flow characteristics

DN, (mm)	$Kv = b * e^{x/a}$, when $\varphi < 75^o$		$Kv = c * x - d$, when $\varphi \geq 75^o$	
	a	**b**	**c**	**d**
40	19,5	1	0,8	4
50	19	1,5	2,2	86
65	21,65	3,5	3,4	134
80	21,3	5	5,1	201
100	20,8	9	6,4	102

As may be seen from the figure, the valve characteristic is nonlinear, the nonlinearity progresses when passage diameter increases. For creating the simplest valve mathematical model, which will be used in rotation angle accounting system, the valve dynamic characteristic data is necessary, and for usage of this model the Kv data and valve rotation angle data at every point of time are required. The approximation formulas obtained to predict butterfly valve flow characteristic are presented in Table 1. The flow characteristic in this form of equation can be regarded as simplest mathematical model of butterfly valve for prediction of its regulating behavior. It is necessary to use this model together with more complex models of plate heat exchanger.

2.2 Mathematical modeling of plate heat exchangers

Let consider the ***steam heated heat exchanger*** , see Shinsky (2008). Steam is the most common heating medium which in condensing transfers its latent heat to flow of heated stream, causing heat load to be proportional to steam flow. For raising a liquid temperature from T_1 to T_2 by condensing steam one can write:

$$Q = G_S \cdot r = G_C \cdot c_{pC} \cdot (T_{C2} - T_{C1}) \qquad (1)$$

where G_S and r are mass flow of steam and its latent heat, G_C and c_{pC} are the mass flow rate and specific heat of heated liquid and Q is the rate of heat transfer. The response of control temperature to steam flow is linear:

$$\frac{dT_{C2}}{dG_S} = \frac{r}{G_C \cdot c_{pC}} \qquad (2)$$

The disturbance of exit liquid temperature ΔT_{C2} will require the compensating change in steam flow rate ΔG_S and, in case of butterfly valve flow control, the rotation of valve shaft on an angle:

$$\Delta\varphi = \frac{\Delta G_S}{\frac{dG_S}{d\varphi}} = \frac{\Delta T_{C2}}{\frac{dG_S}{d\varphi}} \cdot \frac{G_C \cdot c_{pC}}{r} \qquad (3)$$

The derivative of flow rate G_S on valve shaft rotation angle can be easily found from characteristic curve (see Fig.2), but it require the determination of the shaft angle position. In the discussed case of steam heating, when the process model is linear, the operation of using this derivative can be also regarded as butterfly valve characteristic linearization. But it is not so straightforward in case when heating or cooling media is liquid and the model became nonlinear. As it is noticed by Shinsky (2008), the equal-percentage control valve can give better results.

Let consider ***the heat exchanger heated by liquid.*** Where there is no condensation, the heat transfer rate is no linear with the flow of manipulated stream. It is a function of mean temperature difference ΔT_m and flow rates of both streams through overall heat transfer coefficient U :

$$Q = UF_a\Delta T_m = G_H c_{pH}(T_{H1} - T_{H2}) = G_C c_{pC}(T_{C2} - T_{C1}) \qquad (4)$$

Where F_a is heat transfer area, subscripts $_H$ and $_C$ refer to the hot and cold streams, respectively. Consider the countercurrent flow, where the cold stream outlet temperature is controlled. The logarithmic mean temperature difference in such heat exchanger:

$$\Delta T_m = \frac{(T_{H1} - T_{C2}) - (T_{H2} - T_{C1})}{\ln\left(\frac{T_{H1} - T_{C2}}{T_{H2} - T_{C1}}\right)} \quad (5)$$

Solving equations (4) and (5) for T_{H2} it can be also obtained:

$$T_{H2} = T_{C1} + (T_{H1} - T_{C1}) \frac{1 - G_H c_{pH} / G_C c_{pC}}{\exp\left[UF_a\left(\frac{1}{G_H c_{pH}} - \frac{1}{G_C c_{pC}}\right)\right] - \frac{G_H c_{pH}}{G_C c_{pC}}} \quad (6)$$

For unsteady conditions the heat balance can be written in simplified form as the heat loss by hot stream equal to heat received by cold stream and heat exchanger system:

$$G_H c_{pH}(T_{H1} - T_{H2}) = G_C c_{pC}(T_{C2} - T_{C1}) + k(M_{HUC} \cdot c_{pC} + M_{HUH} \cdot c_{pH} + M_{HE} c_{HE})\frac{dT_{C2}}{dt} \quad (7)$$

Where t – time, s; M_{HE} - total mass of heat exchanger, kg; c_{HE} - average heat capacity of heat exchanger material J/kgK; M_{HUC} and M_{HUH} - mass hold ups of heat exchanger on cold and hot side respectively; k – proportionality coefficient accounting for proportionality of average heat exchanger temperature to exit temperature of cold stream. This coefficient can be determined during model identification process on real heat exchanger.

2.3 Mathematical model for unsteady state

Equation (7) can be rewritten as:

$$\frac{dT_{C2}}{dt} = A - B \cdot T_{C2} \quad (8)$$

where:

$$A = \frac{1}{kM_{HE}c_{HE}}\left[G_H c_{pH}(T_{H1} - T_{H2}) + G_C c_{pC} T_{C1}\right]; \; B = \frac{G_C c_{pC}}{k(M_{HUC} \cdot c_{pC} + M_{HUH} \cdot c_{pH} + M_{HE} c_{HE})} \quad (9)$$

Integrating this ordinary differential equation from initial time $t_0 = 0$ to t_X we get for temperature T_{C2X} at moment x:

$$T_{C2X} = \frac{A}{B} - \left(\frac{A}{B} - T_{C20}\right) \cdot \exp(-B \cdot t_X) \quad (10)$$

Here parameter A/B is characterized by the temperatures and flow rates of heat exchanging streams. Parameter B is characterized as ratio of cold stream heat capacity to heat capacity of heat exchanger system. Identifying parameter k from real heat exchanger tests or from more complex model analysis we can use equation (10) for establishing control strategy of heat exchanger.

Let assume that the process is slow and with some approximation the outlet temperature at any moment can be estimated by formula (6). In this case the equation (10) represents the simplified mathematical model of unsteady behavior of heat exchanger. It should be accompanied by equation (6) and others for calculation of overall heat transfer coefficient U.

To identify parameter k of the model the test was performed on pilot unit installed on district heating substation, which is described below. The time of achieving steady state temperature conditions after opening the valve from completely closed position was measured. The result was compared with calculation on developed mathematical model. The good agreement was reached at the value of parameter k=0.9, which can be used for further work with model.
For modeling of plate heat exchanger more detailed complex models like presented in paper of Georgiadis and Macchietto (2000) can also be used. But as was shown, for district heating application the one described here gives results sufficient for control of temperature in the range ± 2 °C.

3. Tests on pilot unit

The pilot unit was fabricated and installed on one of District Heating substations with Alfa-Laval M10 plate heat exchanger for Hot Tap Water heating in Kharkiv, Ukraine. The butterfly valve of DN 40 mm was used.To obtain the valve rotation angle the transmitter is situated directly on the valve shaft. In this case the magnetoresistor HMC1512 produced by Honeywell is used. It determines rotation angle in 90° and more. HMC1512 involves two bridges. The signal from magnetoresistor is transmitted to analog to digital converter, which proceeds received data and transmits it to the microcontroller ATMega32L. The interaction of components is shown on Figure 2.

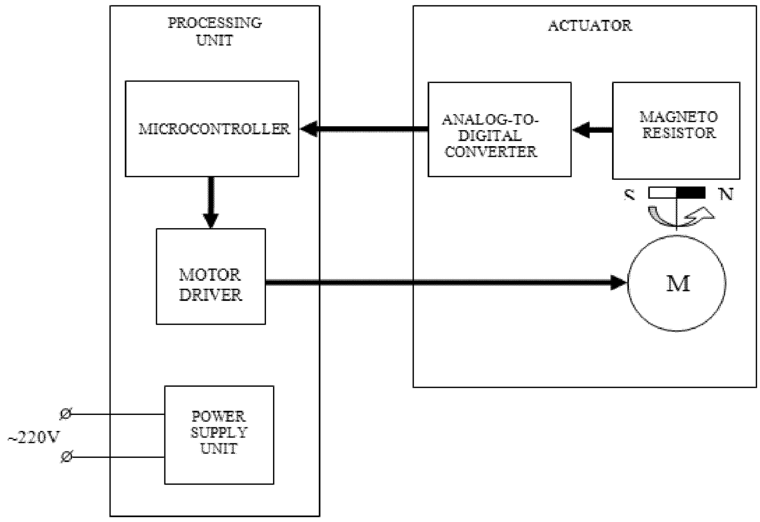
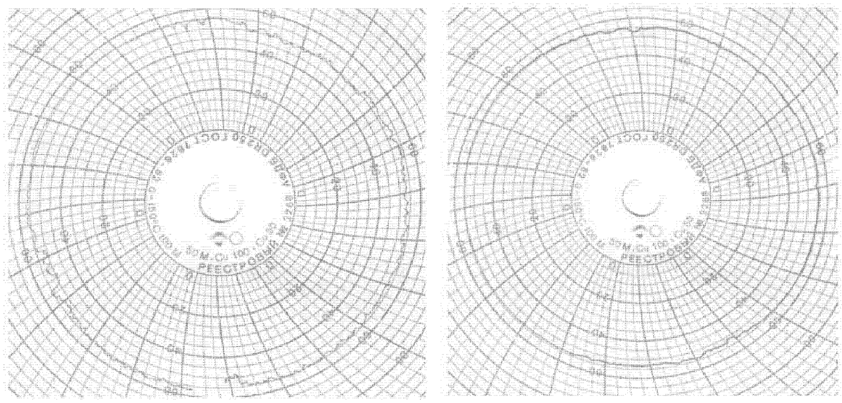


Figure 2. Block diagram of processing unit and actuator interaction

Controller is producing impulses for the actuator in order to reach the preset value of temperature. The impulse time depends on system response. When approaching the preset value of controlled parameter, the impulse duration decreases according to accuracy requirement.

During the tests the outlet temperature from the heat exchanger was recorded by standard disk-shaped recorder during 24 hours. The comparison of results obtained in two runs, with and without rotation angle accounting system, are presented on Figure 2. It is shows the significant, up to 2.5 times, improvement of temperature control accuracy.



a b

Figure 2. Results of regulator control quality testing: a- standard PID strategy; b- parametric model predictive control with rotation angle accounting

4. Conclusion

The parametric model predictive control technique with rotation angle accounting system enables to significantly improve the temperature control quality of the regulator based on butterfly valve. It decreases common oscillation of system and optimizes system impact on change of value of controlled parameter.

Acknowledgments

The support from an EC FP6 Framework project CONNECT (Design of Advanced Controllers for Economic, Safe and Robust Manufacturing Performance, Contract No: 031638) is gratefully acknowledged.

References

Georgiadis M.C., Macchietto S., 2000, Chemical Engineering Science. 55; 1605-1619.

Shinsky F.G.,2008, Unit Operations Control. In: Green D.W., Perry R.H., eds. Perry's Chemical Engineers Handbook, 8^{th} edn. McGrow-Hill, New-York; 839-847.

Sakizlis V., Dua V., Perkins J.D., Pistikopoulos E.N., 2004, Computers and Chemical Engineering, 28; 195.

Waite A.W.R., Eng P., 2008, Controllers, Final Control Elements and Regulators. In: Green D.W., Perry R.H., eds. Perry's Chemical Engineers Handbook, 8^{th} edition. McGrow-Hill, New-York; 871-896.