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Control of milk pasteurization process using model predictive approach

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ABSTRACT

A milk pasteurization process, a nonlinear process and multivariable interacting system, is difficult to control by the conventional on–off controllers since the on–off controller can handled the temperature profiles for milk and water oscillating over the plant requirements. The multi-variable control approach with model predictive control (MPC) is proposed in this study. The proposed algorithm was tested for control of a milk pasteurization process in four cases of simulation such as set point tracking, model mismatch, difference control and prediction horizons, and time sample. The results for the proposed algorithm show the well performance in keeping both the milk and water temperatures at the desired set points without any oscillation and overshoot and giving less drastic control action compared to the cascade generic model control (GMC) strategy.

1. Introduction

Pasteurized milk, a dairy product, has a shelf life of 8–10 days in an unopened package. Food safety is a concren in milk temperature at every stage of the pasteurized milk process, especially at the heat treatment process. It is clearly defined as above 72 °C heating temperature at the outlet of the holding tube and below 4 °C cooling temperature at the cooling stage of the plate pasteurizer (PP). Consequently, the control system has been designed to ensure the safety of pasteurized milk.

The control system in Thailand pasteurized milk plant, which was visited, has been used individually automatic control approaches at process equipment involved including utilities (Niamsuwan, Kittisupakorn, & Mujtaba, 2011). The conventional on–off controllers have been applied to keep the water temperature in the boiler and the ripple plate, respectively. The simulation study validated by the real observation is illustrated in Fig. 1. In spite of the acceptable control performance achieved by the on–off controller, the fluctuated dynamic profiles of the water and milk temperature around the desired set points and the sudden movement control action are frequently presented. It has caused the pasteurized milk plant to insufficiently consume the energy.

The milk pasteurization process presents many challenging control problem, including: nonlinear dynamic behavior: multivariable interaction between manipulated and controlled variables and constraints on manipulated and state variables. A number of control approaches and algorithm that are able to handle some of the above problem have been presented in the academic literature. The single and multivariable controls with cascade standard PID (proportional-integral-derivative) controllers were proposed to eliminate the fluctuation of the milk temperature which was caused by disturbances such as inlet milk temperature, milk flowrate, hot water temperature, hot water flowrate (Morison, 2005; Negiz, Cinar, Schlesser, Ramanauskas, & Armstrong, 1996). Both control algorithms gave good disturbance rejection at the PP. Practically, not only the temperature control but also the level control was required for several process equipments, such as storage tanks. A programmable logic controller known as PLC, programmed in ladder logic, can only be applied for both level and temperature control at a diary plant (Bylund, 1995). One literature has been reported the multivariable control system of milk pasteurization process by Negiz, Ramanauskas, Çinar, Schlesser, and Armstrong (1998). They described the implementation of lethality-based control system for high temperature-short time (HTST) pasteurizer. It performed the significant improvement in control performance over single loop control.

The model predictive control (MPC), one of model-based control approaches, was developed by Culer at Shell Oil Company in 1979. The first approach called as the dynamic matrix control (DMC) based on linear models at that time. Recently, there are many frameworks developed under the predictive control strategy. Nonlinear MPC, a development of conventional MPC, used a nonlinear model (the first-principles mathematical models or semi-empirical models) to deal with nonlinearities in process dynamics and in objective functions (Dones, Manenti, Preisig, & Ferraris, 2010;

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Nomenclature

$A_{pp1}, A_{pp2}, A_{pp3}, A_{pp4}$ transferred area at each stage of PP
A_b, A_{rp} surface area at boiler and ripple plate
A_h transferred area for heating coil at water storage tank
A_f peripheral flow area of ripple plate's compressor
$C_{pm}, C_{ph}, C_{pi}, C_{pt}$ heat capacity for milk, hot water, iced water, and tap water
d_f impeller's diameter for compressor at ripple plate
d_p diameter of holding tube
E evaporation rate for cooling tower
F_m volumetric flowrate of milk
F_h, F_{h1} volumetric flowrate of hot water
F_i volumetric flowrate for iced water
F_t, F_c, F_w volumetric flowrate for tap water, circulation water, and makeup water at cooling tower
h_A heat transfer coefficient at water surface
h_{fg} latent heat vaporization of refrigerant at ripple plate
h_v latent heat vaporization of water
K_1, K_2 tuning constants for GMC
L_d mechanical drift loss at cooling tower
H_f heating value of fuel
m_f fueling rate at boiler
M, P control and prediction horizon for MPC
n sample the process outputs
n_s impeller's rotation speed for compressor at ripple plate
T_{mi}, T_{mo} temperature of milk at inlet and outlet
T_{hi}, T_{ho} temperature of hot water at inlet and outlet
T_{ii}, T_{io} temperature of iced water at inlet and outlet
T_{ti}, T_{to} temperature of tap water at inlet and outlet
T_w temperature of makeup water at cooling tower
t time
t_f terminal time of horizon
u_1, u_2, u_3, u_4 manipulated variable
U_{pp1}, U_{pp2}, U_{pp3}, U_{pp4} overall heat transfer coefficient between both sides at each stage of PP
U_p overall heat transfer coefficient at surface of holding tube
U_b, U_{rp} overall heat transfer coefficient at surface for boiler and ripple plate
U_h overall heat transfer coefficient at surface for heating coil at water storage tank
V_b, V_{rp}, V_{ct} water volume for boiler, ripple plate, and cooling tower
$V_{pp1}, V_{pp2}, V_{pp3}, V_{pp4}$ fluid volume for each side at each stage of PP
V_h water volume inside heating coil at water storage tank
W_1, W_2 weighting factors for MPC
Y measured variables
Y_{sp} desired set points

Greek letters
$\rho_m, \rho_h, \rho_i, \rho_t$ density for milk, hot water, iced water, and tap water
ν specific volume of refrigerant at the exit
ΔT temperature difference between both fluids

Manenti, 2011). Almost conventional MPCs compute the manipulated input values by minimizing the cost function based on optimal steady-state values. For a time-varying process operation, economic model predictive approaches have been developed

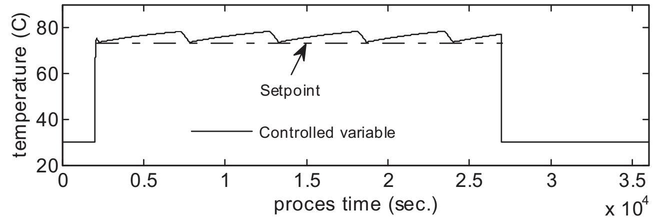

Fig. 1. Temperature profiles for the milk at the outlet of holding tube controlled by with the conventional controller.

by a reformulation of the quadratic cost functions in which the economics-based (not necessarily quadratic) cost function e.g. an estimator-based economic MPC, a Lyapunov-based economic MPC (Chen, Heidarinejad, Liu, & Christofides, 2012; Heidarinejad et al., 2012). The MPC performed many potential applications in the process industry (Bauer & Craig, 2008; Konakom, Kittisupakorn, & Mujtaba, 2008; Kittisupakorn, Thitiyasook, Hussain, & Daosud, 2009; Qin & Badgwell, 2003), but only report of the DMC for HTST pasteurization process has been found (Ibarrola, Sandoval, Garcíia-Sanz, & Pinzolas, 2002).

The MPC technique for multi-input multi-output (MIMO) system is studied in this paper for application to the milk pasteurization process which is commonly found in the dairy industries of Thailand. The highly nonlinear dynamic behavior, multivariable in nature, and interaction between unit processes cause this process to be difficult to control by conventional controllers. Therefore, the aim and contribution of this work is at showing the applicability of the nonlinear MPC on a multivariable process referring to a real industrial plant. To demonstrate the robustness of the predictive control strategy, tests involving set point tracking based on the real operation including model mismatch are performed in this study. Comparison is also made for the GMC approach.

2. Process description

The milk pasteurization process can be briefly introduced. It consists of the unit process involved including utilities: PP, holding tube, boiler, cooling tower, ripple plate, and three water tanks as shown in Fig. 2. The mathematical models of milk pasteurization process have been studied here (Niamsuwan, Kittisupakorn, & Mujtaba, 2013). The meaning of letters and symbols are given in nomenclature. The physical properties, geometry characteristics, and process data are summarized in Table 1.

$$\frac{dT_{mo}}{dt} = \frac{F_m(T_{mi} - T_{mo})}{V_{pp,i}} \pm \frac{U_{pp,i}A_{pp,i}\Delta T_i}{\rho_m C_{pm} V_{pp,i}} \quad (1)$$

$$\frac{dT_{hi,1}}{dt} = \frac{(1-u_1)F_h(T_{ho} - T_{hi,1})}{V_{pp,2}} - \frac{U_{pp,2}A_{pp,2}\Delta T_2}{\rho_h C_{ph} V_{pp,2}} \quad (2)$$

$$\frac{dT_{ti}}{dt} = \frac{F_t(T_{to} - T_{ti})}{V_{pp,3}} + \frac{U_{pp,3}A_{pp,3}\Delta T_3}{\rho_t C_{pt} V_{pp,3}} \quad (3)$$

$$\frac{dT_{ii}}{dt} = \frac{u_2 F_i(T_{io} - T_{ii})}{V_{pp,4}} + \frac{U_{pp,4}A_{pp,4}\Delta T_4}{\rho_i C_{pi} V_{pp,4}} \quad (4)$$

$$T_{mo} = T_{mi} + \frac{4U_p(T_{mo} - T_a)}{\rho_m C_{pm} d_p} \quad (5)$$

$$\frac{dT_{to}}{dt} = \frac{F_t(T_{ti} - T_{to})}{V_{ct}} - \frac{h_v E}{C_{pt} V_{ct}} + \frac{\rho_w C_{pw} F_w T_w}{\rho_t C_{pt} V_{ct}} - \frac{L_d F_c T_{ti} + h_A(T_{to} - T_a)}{\rho_t C_{pt} V_{ct}} \quad (6)$$

$$\frac{dT_{io}}{dt} = \frac{u_2 F_i(T_{ii} - T_{io})}{V_{rp}} + \frac{\pi(u_4 n_s) d_f h_{fg} A_f}{60\rho_i C_{pi} V_{rp} \nu} - \frac{U_{rp}A_{rp}(T_{io} - T_a)}{\rho_i C_{pi} V_{rp}} \quad (7)$$