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A computer based solution to check the drop in milk outlet temperature due to fouling in a tubular heat exchanger

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Abstract

Milk fouling is the main cause of progressive decline in the rate of heat transfer in a UHT milk sterilizer, which results in a drop in milk outlet temperature as the processing advances. Increasing steam temperature is one of the ways to overcome the drop in milk outlet temperature and prolong the operating time before the processing is stopped for cleaning of deposits in the heat exchanger. A computer model is developed for accurate control of milk temperature as affected by fouling. It can calculate accurately the increase in steam temperature required for maintaining the desired milk sterilization temperature. The results with steam control are compared with the results without any control and this procedure was found satisfactory for controlling the milk outlet temperature. The procedure described can be applied to any heat exchanger with minor modifications, if necessary.

Keywords: Milk; Fouling; Model; Heat exchanger; UHT; Steam

1. Introduction

Processing of UHT milk is normally carried out commercially in indirect heating plants in which the temperature of milk is raised by passage through a tubular heat exchanger. In such a plant, the quantity of milk that can be processed between two successive cleaning operations is limited by the amount and rate of deposition of fouling material. Under modern processing conditions most fouling generally occurs in the hottest regions of the plant (120–140 °C) (Burton, 1968; Grandison, 1988). Deposit formation results in the build up of high-pressure in the heat exchanger and thermal efficiency is also reduced (Burton, 1968; Swartzel, 1983). Fouling not only results in higher operating costs but has an adverse effect on environment also (Brinkmann, 1986; Graßhoff, 1997; Sandu & Singh, 1991; Visser & Jeurnink, 1997). Various factors influencing the deposit formation in UHT processing include fore-warming of milk (Bell & Senders, 1944; Lyster, 1965; Burton, 1966; Mottar & Moermans, 1988; Patil & Reuter, 1986a, 1986b), pre-pasteurization (Lalande, Tissier, & Corrieu, 1984), pH of milk (Burton, 1966; Gordon, Hankinson, & Carver, 1968; Gynning, Thome, & Samuelsson, 1958; Kastanas, Lewis, & Grandison, 1995; Patil & Reuter, 1988; Skudder, Brooker, Bonsey, & Alvarez Guerrero, 1986), air content (Jeurnink, 1995; Tirumalesh, Rao, & Jayaprakash, 1997), surface material (Foster, Britten, & Green, 1989; Foster & Green, 1990; Jeurnink, Verheul, Cohen, & de Kruif, 1996; Sharon & Fuller, 1994; Visser, Jeurnink, Schraml, Fryer, & Delplace, 1997) total solids, age of milk, season, addition of oxidizing agents (iodate, H_2O_2, dichromate) (Marshall, 1986; Skudder, Thomas, Pavey, & Perkin, 1981), addition of free fatty acids (Al-roubale & Burton, 1979), addition of phosphates (Burdett, 1974), etc.

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Nomenclature

Bi_{mi}	Biot number due to outer surface of innermost tube, dimensionless
Bi_{mo}	Biot number due to inner surface of middle tube, dimensionless
C_{pf}	specific heat of working fluid, J/kg K
E_i	activation energy on outer surface of innermost tube, J/mol
E_o	activation energy on inner surface of middle tube, J/mol
$f(Bi_{mi})$	function of Bi_{mi}
$f(Bi_{mo})$	function of Bi_{mo}
g	acceleration due to gravity, 9.81 m/s^2
h_{c1}	steam/condensate heat transfer coefficient due to innermost tube, W/m^2 K
h_{c2}	steam/condensate heat transfer coefficient due to outermost tube, W/m^2 K
h_f	film heat transfer coefficient with fouled layer present, W/m^2 K
h_f^o	film heat transfer coefficient without fouling, W/m^2 K
i	index
j	index
k_d	thermal conductivity of fouled layer, W/m K
k_{di}	deposition rate constant due to outer surface of innermost tube, l/s
k_{do}	deposition rate constant due to inner surface of middle tube, l/s
k_{ri}	removal rate constant due to outer surface of innermost tube, l/s
k_{ro}	removal rate constant due to inner surface of middle tube, l/s
k_s	thermal conductivity of stainless steel, W/m K
L	length of tube, m
N	number of nodes
R	universal gas constant, 8.314 J/mol K
r_{d1}	radius up to fouled layer due to outer surface of innermost tube, m
r_{d2}	radius up to fouled layer due to inner surface of middle tube, m
r_{i1}	inner radius of innermost tube in HTTHE, m
r_{i2}	inner radius of middle tube in HTTHE, m
r_{o1}	outer radius of innermost tube in HTTHE, m
r_{o2}	outer radius of middle tube in HTTHE, m
t	time, s
T_f	process fluid temperature, K
T_{d1}	temperature at the interface of fouling deposit and process fluid on outer surface of innermost tube, °C
T_{d2}	temperature at the interface of fouling deposit and process fluid on inner surface of middle tube, °C
T_s	temperature of steam, °C
U_{i2}	overall heat transfer coefficient due to inner surface of middle tube in heating section with fouling, W/m^2 K
U_{i2}^o	overall heat transfer coefficient due to inner surface of middle tube in heating section without fouling, W/m^2 K
U_{o1}	overall heat transfer coefficient due to outer surface of innermost tube in heating section with fouling, W/m^2 K
U_{o1}^o	overall heat transfer coefficient due to outer surface of innermost tube in heating section without fouling, W/m^2 K
v_f	average velocity of process fluid, m/s
$\Delta\alpha$	time interval, s
ϕ_{mi}	film coefficients and thermal conductivity ratio for outer surface of innermost tube, dimensionless
ϕ_{mo}	film coefficients and thermal conductivity ratio for inner surface of middle tube, dimensionless
ρ_f	density of process fluid at mean temperature, kg/m^3
γ_f	kinematic viscosity of the process fluid, m/s

A number of attempts have been made earlier to cope with the problem of fouling which include design of fouling resistant equipment i.e. scraped surface heat exchanger, advanced clean-in-place (CIP) techniques to remove deposit easily and various controls on processing parameters. A new type, the cartridge exchanger (Margettai, 1985) was designed so that product flows faster and more evenly than in a plate heat exchanger. Alternative processes also resist fouling: in the APV Baker ohmic heating process (Skudder & Biss, 1987) foods are heated by direct application of electric current. de Alwis, Halden, and Fryer (1989) show that the electrodes are at a lower temperature than the bulk of the food; fouling is thus reduced in the absence of hot surfaces. Several researchers (De Jong, 1996; Delplace & Leuliet, 1995; Fryer, 1989; Georgiadis, Rotstein, & Macchietto, 1998a, Georgiadis, Rotstein, & Macchietto, 1998b; Robbins, Elliot, Fryer, Belmar, & Hasting, 1999; Taborek, Aoki, Ritter, Palen, & Knudsen, 1972; Toyoda, Schreier, & Fryer, 1994) have tried to model heat exchanger fouling and potential cost saving up to 50% have been reported (De Jong, 1996; De Jong, te Giffel, Straatsma, & Vissers, 2002). Experiments (Fryer, 1989) have shown that fouling is minimized by low wall temperature, high fluid velocities and turbulence, giving low fluid residence times at the wall and a low thermal boundary layer thickness. To resist fouling, rough surfaces should be avoided (Baier, 1981). Fryer and Slater