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Milk fouling simulation in helical triple tube heat exchanger

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Abstract

Heat exchanger fouling is a common phenomenon during high temperature processing of milk. The temperature of milk raises from 90 °C to 150 °C during Ultra-High-Temperature (UHT) sterilization process. At such high temperature, the minerals and denatured proteins deposit on the heat exchanger surface, also known as fouling. Fouling acts as resistance to heat transfer, hence the performance of the heat exchanger is reduced. Using hydrodynamics and heat balance concept, a mathematical model was formulated. Simulation was performed with the model to predict the fouling behavior as a function of time and position within the helical triple tube heat exchanger (HTTHE). At an early period of operation, the uniform fouling deposit occurs throughout the length of the heat exchanger due to constant heat exchanger wall temperature. With progress of time, the fouling deposit and also Biot number (i.e., local fouling factor) increases towards the outlet of the heat exchanger since the interface temperature between fouling deposit and milk approaches towards the bulk milk temperature, that increases towards the heat exchanger outlet. The fouling deposit stabilizes after 105 min since no net deposit occurs after that time.

Keywords: Milk; Fouling; Simulation; Helical triple tube; Heat exchanger; UHT

1. Introduction

UHT sterilization of milk means heating milk by a continuous process to 135–150 °C and holding it for a few seconds. The sterilized milk is not completely free of organisms. It is free of sporulating, toxicogenic and pathogenic organisms to a level so that it remains safe for consumption for several weeks at room temperature (Pien, 1955). The electrochemical deposition of milk solids such as denatured proteins and mineral salts, is most severe in the temperature range of 90–120 °C (Burton, 1988). Since a tubular heat exchanger is likely to maintain a constant wall temperature of 160 °C, the deposition on the heat exchanger surface is a serious problem for UHT sterilizers. Fouling layers increase the heat transfer resistance, which leads to reduction of milk outlet temperature. Fouling also reduces the flow area of milk so that pressure drop increases. Since fouling reduces the continuous run time of a heat exchanger, hence frequent cleaning is needed. Although many researchers and scientists all over the world have already worked and developed lots of fouling models, the actual mechanism of fouling is yet to be known. After surveying numerous fouling mechanisms (Changani, Belmar-Beiny, & Fryer, 1997; Taborek, Aoki, Ritter, Palen, & Knudsen, 1972a) it is suggested to develop a fouling model considering flow pattern and temperature of the process plant. According to Visser and Jeurnink (1997) the very high flow rates of fluid can be able to prevent its solids deposition and subsequent sticking. A series of possible scale up strategies (i.e., constant Reynolds number, constant

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Nomenclature

A_f	area of flow of process fluid, m^2
A_{i2}	heat transfer surface area based on inside diameter of middle tube, m^2
A_{o1}	heat transfer surface area based on outside diameter of innermost tube, m^2
Bi	Biot number, dimensionless
Bi_{mi}	Biot number at outer surface of innermost tube, dimensionless
Bi_{mo}	Biot number at inner surface of middle tube, dimensionless
C_{Pf}	specific heat of process fluid at mean temperature, J/kg K
D_c	coil diameter, m
D_{eq}	equivalent diameter of tube, m
D_{i1}	inner diameter of innermost tube, m
D_{i2}	inner diameter of middle tube, m
D_{o1}	outer diameter of innermost tube, m
E	activation energy, J/mol
f	friction factor, dimensionless
g	acceleration due to gravity = 9.81 m/s^2
h_{c1}	steam/condensate heat transfer coefficient at surface of innermost tube, W/m^2 K
h_{c2}	steam/condensate heat transfer coefficient at surface of outermost tube, W/m^2 K
h_f	film heat transfer coefficient with fouling, W/m^2 K
h_f^0	film heat transfer coefficient without fouling, W/m^2 K
λ_c	thermal conductivity of condensate, W/m K
k_d	deposition rate constant, s^{-1}
k_r	removal rate constant, s^{-1}
L	length of tube, m
N	number of nodes
N_{DN}	dean number, dimensionless
$(N_{DN})_{critical}$	critical dean number, dimensionless
N_{Nu}	Nusselt number, dimensionless
N_{Pr}	Prandtl number, dimensionless
N_{Re}	Reynolds number, dimensionless
Q	flow rate of process fluid, m^3/s
q	heat transfer rate, W
R	universal gas constant = 8.314 J/mol K
r_{d1}	outer radius of innermost tube including fouling layer on its outer surface, m
r_{d2}	inner radius of middle tube including fouling layer on its inner surface, m
r_{i1}	inner radius of innermost tube, m
r_{o1}	outer radius of innermost tube, m
r_{i2}	inner radius of middle tube, m
r_{o2}	outer radius of middle tube, m
t	time, s
T_f	temperature of process fluid, °C
T_f^{IN}	initial temperature of process fluid, °C
T_{fi}	temperature at the interface of fouling deposit and process fluid, °C
T_{i1wall}	temperature of wall at inner side of innermost tube, °C
T_{i2wall}	temperature of wall at outer side of middle tube, °C
T_s	temperature of steam, °C
U_{i2}	overall heat transfer coefficient for the inner surface of middle tube in helical triple tube heat exchanger with fouling, W/m^2 K
U_{i2}^0	overall heat transfer coefficient for the inner surface of middle tube in helical triple tube heat exchanger without fouling, W/m^2 K
U_{o1}	overall heat transfer coefficient for the outer surface of innermost tube in helical triple tube heat exchanger with fouling, W/m^2 K
U_{o1}^0	overall heat transfer coefficient for the outer surface of innermost tube in helical triple tube heat exchanger without fouling, W/m^2 K