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PREDICTION OF FOULING THICKNESS AND BULK MILK OUTLET TEMPERATURE BY ARTIFICIAL NEURAL NETWORK (ANN) MODELING IN HELICAL TRIPLE TUBE MILK STERILIZERS

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ABSTRACT

An ANN model is implemented on helical triple tube UHT milk sterilizers and results are validated with the actual measured data. The scale-up strategy used here is successful in predicting the results for the other heat exchangers. The neural network developed is predicting data accurately with root mean square error (RMSE) in order of 10^{-4}. It is found that for the response of outlet temperature, the effect of Reynolds number is the highest, where as for fouling layer thickness the effect of time is the maximum. The fouling thickness reduces as the diameter increases; this may be due to the increase in surface area for heat transfer with the increase in diameter and length. This model can be very useful for predicting the long-term behaviour of tubular UHT milk sterilizers used in industries.

INTRODUCTION

Milk fouling has become a problem of great practical significance as far as plant sanitation is concerned. A more important effect is the possible limitation of the time for which a heat treatment plant can be operated without intermediate cleaning. The operating time may be restricted either through the deposits obstructing the flow passage in the heat exchanger, so causing excessive pressure drop or through reduction of the heat transfer coefficients for heating surfaces (milk deposits are invariably poor thermal conductors), so making it increasingly difficult to maintain the required processing temperature. Besides qualitative losses of the food, product's microbial safety is not guaranteed. Deposit formation thus increases the energy costs of the plant, and therefore to improve the operating efficiency and to ensure product safety, frequent cleaning is necessary, which is economically undesirable as it reduces the availability of expensive plant and increases the processing costs. Also the problem of deposit formation manifests itself economically through the time and materials required to clean the solid surfaces and through loss of products and losses of minerals and other nutrients in the deposit layer. The additional annual costs in the dairy industry caused by fouling are estimated at 260 million Euro in Europe (Brinkmann, 1986) and in USA fluid milk industry (pasteurized milk production, i.e. no sterilized and ultra high temperature milk) at $140 millions per year, approximately at current prices (Sandu and Singh, 1991). Two decades earlier, the total fouling cost in the U.S. industries was estimated to be $400–700 million per year (Rebello et al.1988). It was also reported that fouling causes a decrease in the efficiency of heat exchangers by 10 to 80% at an average of 26%. Cattel (1981) reported that the problem of fouling has been so serious that the plate heat exchanger cannot be run for more than five hours continuously due to the limitations of pressure imposed on the rubber gaskets.

Ranjan and Datta (1999) and Sahoo et al. (2005) simulated the fouling behaviour as a function of time and position within the double concentric tube heat exchanger. Hydrodynamics and heat balances are used to formulate two independent differential equations expressing bulk milk temperature and fouling thickness as function of time and position. The important observation was found that the fouling thickness stabilized after 0.7h. Toyoda et al. (1994) proposed the application of fouling model to both heating and cooling situations. In the heating situations it was shown that the experimental deposit profile could be matched reasonably well by assuming either the denatured (unfolded) protein, or aggregated protein or both separately as the only foulant. In the cooling section, however, the original model did not produce obvious decaying profile. Even with the incorporation of the reversible step of the protein denaturation, the model did not produce what was often witnessed in the factory. This indicates that the deposition rate constant must be a temperature dependent variable, which reduces to, as the wall temperature approaches to a value where there is visibly no fouling on the surface. Experimental data were obtained by Schraml et al. (1996) and used to model the rate of deposit formation as a function of time. A more complex model incorporating the temperature difference between the bulk fluid and boundary layer of the fluid, the protein chemistry, mass transfer and wall reaction is reported by Schreier and Fryer (1995) for determination of the deposit mass growth rate. A numerical procedure based on the method of characteristics was presented by Fryer and Slater (1985). For the simulation of the average overall heat transfer behaviour of a heat exchanger, which is subjected to chemical reaction fouling, the constitutive heat exchanger equations were directly integrated together with an equation that described the local fouling rate at a point on the heat transfer surface. The procedure was demonstrated for fouling of tubular heat exchanger by skimmed milk employing an experimentally determined local fouling rate model. A performance calculation for four different exchangers was presented to illustrate aspects of fouling behaviour. Jun and Puri (2005) have presented a considerable amount of work on modeling of the fouling process as well as the hydrodynamic and thermodynamic performances of heat exchangers. They have summarized the available information on existing fouling models in terms of fouling mechanisms, dynamic performances of heat exchangers and integrated fouling dynamics. Summarizing these approaches, it is obvious that only few of them considered the composition of the product, in addition to that, most models are only developed for pasteurization conditions. Hence the effects at UHT temperatures are not taken into account. Afgan and Carvelho(1996) designed a knowledge based expert system for assessment of fouling in heat exchangers. The fouling layer thickness was predicted on the basis of reduced effectiveness. The effectiveness was measured in terms of NTU. Heat exchanger dimension and hot and cold fluid flow rates at different operating conditions were taken as input for the fouling layer thickness prediction. Zhou and Zhang (2003) devised a method for online measurement of fouling layer thickness in brewery wort evaporator using a soft sensing approach. The factors affecting fouling were temperature, pH, turbidity and viscosity of the wort, temperature of heating vapor, flow rate of heating vapor and pressure in evaporator.

Considering all the above points following objectives were taken up – (i) to train ANN using data available from a laboratory model milk sterilizer; (ii) to optimise the network architecture for minimum deviation in predicted result; (iii) to predict the relative importance of independent variables on outlet temperature and fouling layer thickness in helical triple tube heat exchanger; (iv) To apply ANN to predict fouling thickness and maximum temperature in helical triple tube heat exchangers operational in industry.

THEORETICAL PRINCIPLES

In helical triple tube heat exchanger (HTTHE), the steam flows in the innermost and the outermost tubes and process fluid flows in annular portion of the middle tube. In heat transfer calculation the basic assumption is that heat lost by steam in heating section is used to increase the temperature of process fluid in the same section. The different modes of heat transfer across the heat exchanger under ideal condition (i.e. non fouling) are as follows – (i) convection heat transfer due to steam condensing on outside surface of the middle tube and inside surface of the innermost tube; (ii) conduction across the middle tube wall to the inside surface of the middle tube and across the inner tube wall to outside surface of the inner tube; (iii) conduction through the fouled layer deposited on the inside or outside surface(s) of the middle tube; (iv) Convection heat transfer through the outer wall of the inner tube and the inner wall of the middle tube. The overall heat transfer is calculated taking the above modes of heat transfer into account. When fluid flows in annular region of tubes, the fluid side convection heat transfer coefficient can be calculated under turbulent flow condition by the following equation:

$$h_f = \left(\frac{k_f}{D_{eq}}\right) 0.027\, N_{\mathrm{Re}}^{0.8}\, N_{\mathrm{Pr}}^{0.33} \left(\frac{D_{i2}}{D_{o1}}\right)^{0.53} \left[1 + 3.5\left(\frac{D_{eq}}{D_c}\right)\right] \qquad (1)$$

Pressure drop in the annulus can be determined from (2) – (4):

$$\Delta P = \Delta P_a + \Delta P_r \qquad (2)$$

$$\Delta P_a = 4\, f_c \frac{L}{D_{eq}} \frac{\rho_f\, v_f^{\,2}}{2} \qquad (3)$$

$$\Delta P_r = \rho_f\, v_f^{\,2} \frac{2 D_{eq}}{D_c} \qquad (4)$$

Friction factor can be calculated by the following expression:

$$f_c = \frac{0.07725}{\left[\log_{10}\left(\frac{N_{\mathrm{Re}}}{7}\right)\right]^2} + 0.01\sqrt{\frac{D_{eq}}{D_c}} \qquad (5)$$

The enthalpy balance in the annulus of a triple tube is given by:

$$A_f \rho_f v_f C_{pf} T_f \delta t - A_f \rho_f v_f C_{pf}\left(T_f + \frac{\delta T_f}{\delta x}\delta x\right)\delta t + U_{o1} A_{o1}\left(T_s - T_f\right)\delta t + U_{i2} A_{i2}\left(T_s - T_f\right)\delta t = A_f \rho_f C_{pf} \frac{\delta T_f}{\delta t}\delta x \delta t \qquad (6)$$

Using characteristics technique as described by Acrivos (1956), equation (6), a partial differential equation can be converted to ordinary differential equation. The ordinary differential form of equation (6) is:

$$\frac{dT_f}{dt} = 2\left[\frac{r_{o1} U_{o1}^o h_f^o}{h_f^o + U_{o1}^o\, f\left(Bi_{mi}\right)\frac{r_{o1}}{r_{i1}}} + \frac{r_{i2} U_{i2}^o h_f^o}{h_f^o + U_{i2}^o\, f\left(Bi_{mo}\right)\frac{r_{i2}}{r_{o2}}}\right]\frac{T_s - T_f}{\left(r_{i2}^2 - r_{o1}^2\right)\rho_f\, C_{pf}} \qquad (7)$$

where,

$$\frac{r_{i1}}{r_{o1}}\left(Bi_{mi} - 1\right) + \frac{h_f^o}{h_f}\frac{r_{i1}}{r_{d1}} = f\left(Bi_{mi}\right) \qquad (8)$$

and,

$$\frac{r_{o2}}{r_{i2}}\left(Bi_{mo} - 1\right) + \frac{h_f^o}{h_f}\frac{r_{i2}}{r_{d2}} = f\left(Bi_{mo}\right) \qquad (9)$$

For developing the model for fouling in helical triple tube UHT milk sterilizer, a model as suggested by Fryer and Slater (1985) for tubular heat exchanger was used with suitable modifications. The basic equations used for deposition rate and description of the modification made in the aforesaid model, are as follows:

$$\frac{dBi_{mi}}{dt} = k_{di} \exp\left[-\frac{E_i}{R\,T_{d1}}\right] - k_{ri}\, Bi_{mi} \tag{10}$$

and,

$$\frac{dBi_{mo}}{dt} = k_{do} \exp\left[-\frac{E_o}{R\,T_{d2}}\right] - k_{ro}\, Bi_{mo} \tag{11}$$

where,

$$Bi_{mi} = \frac{h_f^o\, r_{o1} \ln\left(\frac{r_{d1}}{r_{o1}}\right)}{k_d} \quad (12) \text{ and } \quad Bi_{mo} = \frac{h_f^o\, r_{i2} \ln\left(\frac{r_{i2}}{r_{d2}}\right)}{k_d} \quad (13)$$

Fouling thickness $\delta = r_{d1} - r_{i1} = r_{i2} - r_{d2}$

Based on the principle of heat flux equivalence concept T_{d1} is substituted in equation (10), then the local overall rate of solids accumulation on outer surface of inner tube can be represented as:

$$\frac{dBi_{mi}}{dt} = k_{di} \exp\left[-\frac{E_i}{R}\frac{\left(\phi_{mi} + f\left(Bi_{mi}\right) + \frac{r_{i1}}{r_{o1}}\right)}{\left(T_s + 273\right)\left(f\left(Bi_{mi}\right) + \frac{r_{i1}}{r_{o1}}\right) + \left[\left(T_f + 273\right)\phi_{mi}\right]}\right] - k_{ri}\, Bi_{mi} \tag{14}$$

Similarly, the local overall rate of solids accumulation on the inner surface of middle tube can be represented as given below:

$$\frac{dBi_{mo}}{dt} = k_{do} \exp\left[-\frac{E_o}{R}\frac{\left(\phi_{mo} + f\left(Bi_{mo}\right) + \frac{r_{o2}}{r_{i2}}\right)}{\left(T_s + 273\right)\left(f\left(Bi_{mo}\right) + \frac{r_{o2}}{r_{i2}}\right) + \left[\left(T_f + 273\right)\phi_{mo}\right]}\right] - k_{ro}\, Bi_{mo} \tag{15}$$

Numerical solution for T_f, Bi_{mi} and Bi_{mo} as functions of position (x) and time (t) were obtained by selecting the number of nodes '*N*' along α-characteristics. The temporal separation of the nodes along α-characteristics was thus set (Ranjan and Datta, 1999) as:

$$\Delta\alpha = \frac{L}{N-1}.\frac{1}{v_f} \tag{16}$$

Initial conditions were set as,

$Bi_{mi}(i, 0)=0$, for $i=1,2,3,\ldots\ldots\ldots N$
$Bi_{mo}(i, 0)=0$, for $i=1,2,3,\ldots\ldots\ldots N$
$T_f(0, j)=T_{in}$, for $j=1,2,3,\ldots\ldots\ldots$

Tube side fluid temperature $T_f(i, j)$ and fouling thickness on the outer wall of the inner tube and the inner wall of the middle tube were obtained. Integration of equations (7), (14) and (15) using Modified Euler's technique gives:

$$T_f(i+1/2, j) = T_f(i, j) + \left.\frac{dT_f}{dt}\right|_{(i,\,j)} \frac{\Delta\alpha}{2} \tag{17}$$

$$Bi_{mo}(i, j+1/2) = Bi_{mo}(i, j) + \left.\frac{dBi_{mo}}{dt}\right|_{(i,\,j)} \frac{\Delta\alpha}{2} \tag{18}$$

$$Bi_{mi}(i, j+1/2) = Bi_{mi}(i, j) + \left.\frac{dBi_{mi}}{dt}\right|_{(i,\,j)} \frac{\Delta\alpha}{2} \tag{19}$$

$$T_f(i+1, j) = T_f(i, j) + \left.\frac{dT_f}{dt}\right|_{(i+1/2,\,j)} \Delta\alpha \tag{20}$$

$$Bi_{mo}(i, j+1) = Bi_{mo}(i, j) + \left.\frac{dBi_{mo}}{dt}\right|_{(i,\,j+1/2)} \Delta\alpha \tag{21}$$

$$Bi_{mi}(i, j+1) = Bi_{mi}(i, j) + \left.\frac{dBi_{mi}}{dt}\right|_{(i,\,j+1/2)} \Delta\alpha \tag{22}$$

The above numerical scheme was applied on an HTTHE having inner tube of 8.5 mm outside diameter, middle tube of 12.7 mm inside diameter and 300 mm coil diameter. T_f, Bi_{mo} and Bi_{mi} were obtained as function of time and position. This result was used as the training model for the ANN. Using tan sigmoid transfer function and multilayer feed forward network was identified with the outputs of the numerical scheme described above. Once the network architecture was finalized the fouling thickness and milk outlet temperatures were obtained for the following heat exchangers:

Table 1. Geometric configuration of heat exchangers used for prediction of fouling thickness and bulk milk outlet temperatures.

Outside diameter of inner tube, mm	Inside diameter of middle tube, mm	Coil diameter, mm
8.5	12.7	300
12	16	320
22	26	440
28	32	510
34	38	580

The seven inputs to the ANN were Reynold Number, Prandtl Number, outside diameter of inner tube, inside diameter of middle tube, coil diameter, pressure drop and HTTHE length.

RESULTS

Experiment was conducted using the smallest heat exchanger listed in Table 1 with skim milk having fat content of 0.5 % and operating under inlet and outlet temperatures of 95 and 145 ^oC with steam at 160 ^oC as the heating agent. The ANN training was carried out with the pressure drop data obtained in the mentioned heat exchanger running with a skim milk flow rate of 130 l h^{-1}. The accuracy of the mathematical model had been established in Nema and Datta (2006). The same was used for validating the Neural Network training results.

Table 2 presents the result of trials of various ANN architectures to indicate that for the 9th trial the normalized RMSE value reaches the minimum of 7.6 x 10^{-5}.

Table 2. Root mean square error (RMSE) as function of ANN architecture.

No.	No. of layers	Input layer neurons	1st hidden Layer neurons	2nd Hidden Layer neurons	Output Layer neurons	RMSE X .0001
1	3	7	2	-	2	128
2	3	7	3	-	2	13.7
3	3	7	4	-	2	15.3
4	4	7	3	1	2	190.3
5	4	7	3	2	2	4.9
6	4	7	3	3	2	7.2
7	4	7	4	1	2	955.7
8	4	7	4	2	2	4.53
9	4	7	4	3	2	0.76
10	4	7	4	4	2	1.07

Table 3. Connecting weights for various inputs (x). 1 – time, 2 – N_{Re}, 3 – N_{Nu}, 4 – d_i, 5 – d_o, 6 – length, 7 – pressure drop.

Input Layer	x	1	2	3	4
	1	-0.020	0.059	-0.138	0.341
	2	0.006	0.008	-0.197	-0.087
	3	-0.003	-0.008	0.202	0.965
	4	-0.335	-0.492	0.229	-0.361
	5	0.546	-0.128	0.284	0.018
	6	-0.267	0.641	-0.570	-0.662
	7	-0.004	0.016	-0.061	-0.480
Hidden Layer 1		1	2	3	
	1	-0.190	-0.034	0.560	
	2	0.840	0.658	0.430	
	3	0.570	0.156	0.700	
	4	-0.912	0.044	-0.357	
Hidden Layer 2		1	2		
	1	0.078	0.123		
	2	0.362	-0.027		
	3	-0.367	0.305		

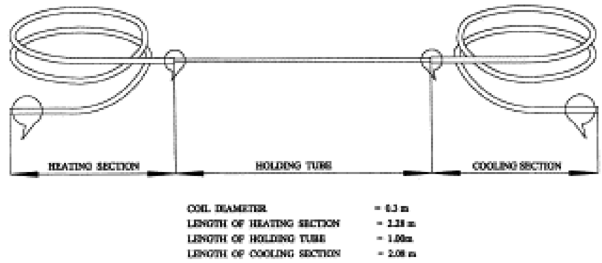

Figure 1. Helical triple tube heat exchanger used for fouling study.

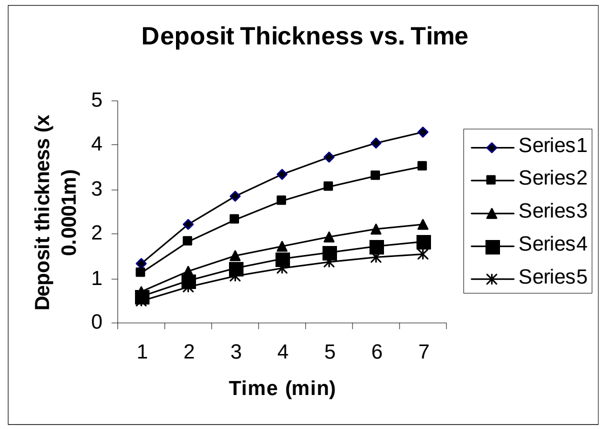

Figure 2. Fouling deposit thickness in mm as function of time of operation (Series 1 is the smallest HTTHE).

Figures 2, 3 and 4 present fouling thickness, outlet temperatures and pressure drops in various HTTHE during the first 7 minutes of operation.

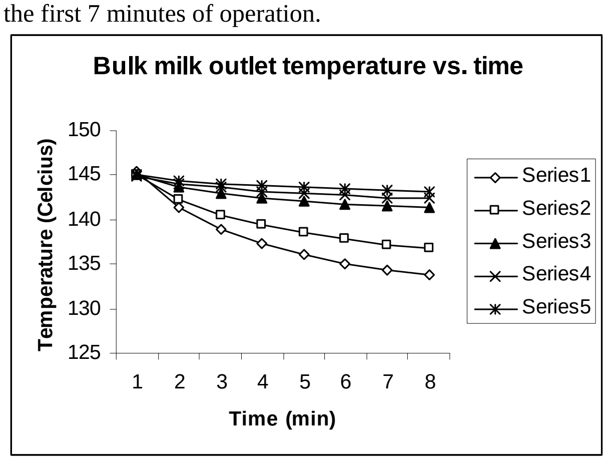

Figure 3. Milk outlet temperatures in ^{o} C as function of time (Series 1 is the HTTHE of smallest dimension).

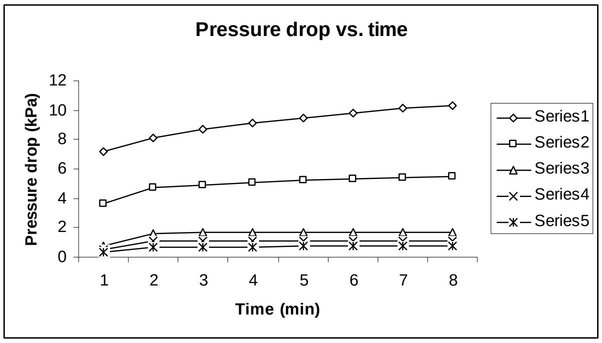

Figure 4. Pressure drop in kPa as function of time (Series 1 is the smallest HTTHE).

DISCUSSION

As evident from the results, the ANN architecture of 7-4-3-2 or 7 input layers followed by 4 first hidden layers before 3 second hidden layers to give 2 output layers provide the least deviation from the trial computed inputs. The figures suggest that fouling is the most severe in the smallest HTTHE. This fact is well demonstrated by the three figures with reduced deposit thickness, smaller outlet temperature deviation from set point and low pressure drops.

CONCLUSIONS

The ANN modeling resulted in a better physical understanding of the fouling mechanism in the milk sterilizer. The results of the model justify bigger HTTHE for milk sterilization as it can handle larger quantity of milk with reduced operational difficulty (Figures 2, 3 and 4). The fouling occurring in the large heat exchanger can be overcome with proper control action of steam pressure elevation to maintain a reasonable duration of operation prior to cleaning the heat exchanger.

NOMENCLATURE

A_f	Area of flow of working 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 the innermost tube, m^2
Bi_{mi}	Modified Biot number on the outer surface of the innermost tube, dimensionless
Bi_{mo}	Modified Biot number on the inner surface of middle tube, dimensionless
C_{pf}	Specific heat of working fluid, J/kg K
C_w	Specific heat of water, J/kg K
d	Characteristic dimension, m
D_c	Coil diameter, m
D_{eq}	Equivalent diameter of tube, m
D_{i2}	Inner diameter of middle tube, m
D_{o1}	Outer diameter of the innermost tube, m
E_i	Activation energy on the outer surface of the innermost tube, kJ/kg mol
E_o	Activation energy on the inner surface of middle tube, kJ/kg mol
f_c	Friction factor, dimensionless
$f(Bi_{mi})$	Function of Bi_{mi}
$f(Bi_{mo})$	Function of Bi_{mo}
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 the outer surface of the innermost tube, l/s
k_{do}	Deposition rate constant due to the inner surface of middle tube, l/s
k_f	Thermal conductivity of milk, W/m-K
k_{ri}	Removal rate constant due to the outer surface of the innermost tube, l/s
k_{ro}	Removal rate constant due to the inner surface of middle tube, l/s
L	Length of tube, m
N	Number of nodes
N_{Pr}	Prandtl number, dimensionless
N_{Re}	Reynolds number, dimensionless
R	Universal gas constant, 8.314 kJ/ kg mol K
r_{d1}	Radius up to fouled layer due to the outer surface of the innermost tube, m
r_{d2}	Radius up to fouled layer due to the inner surface of middle tube, m
r_{i1}	Inner radius of the innermost tube in HTTHE, m
r_{i2}	Inner radius of middle tube in HTTHE, m
r_{o1}	Outer radius of the innermost tube in HTTHE, m
r_{o2}	Outer radius of middle tube in HTTHE, m
t	Time, s
T_{d1}	Temperature at the interface of fouling deposit and process fluid on the outer surface of innermost tube, ^{o}C
T_{d2}	Temperature at the interface of fouling deposit and process fluid on the inner surface of middle tube, ^{o}C
T_f	Process fluid temperature, ^{o}C
T_s	Temperature of steam, ^{o}C

U_{i2}	Overall heat transfer coefficient due to the inner surface of middle tube in heating section with fouling, W/m^2-K
U_{i2}^{o}	Overall heat transfer coefficient due to the inner surface of middle tube in heating section without fouling, W/m^2-K
U_{o1}	Overall heat transfer coefficient due to the outer surface of the innermost tube in heating section with fouling, W/m^2-K
U_{o1}^{o}	Overall heat transfer coefficient due to the outer surface of the innermost tube in heating section without fouling, W/m^2-K
v_f	Average velocity of process fluid, m/s
δ	Thickness of fouling layer, m
$\Delta\alpha$	Time interval, s
ΔP	Pressure drop, Pa
ΔP_a	Axial pressure drop, Pa
ΔP_r	Radial pressure drop, Pa
δt	Finite time interval, s
δx	Finite length of element, m
ϕ_{mi}	Film coefficients and thermal conductivity ratio for the outer surface of the innermost tube, dimensionless
ϕ_{mo}	Film coefficients and thermal conductivity ratio for the inner surface of the middle tube, dimensionless
ρ_f	Density of process fluid at mean temperature, kg/m^3

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