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Computer Aided Design of an Indirect Type UHT Heat Exchanger

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ABSTRACT

Ultra High Temperature (UHT) sterilization process involving indirect type heating has an advantage of simplicity in design and operation. Indirect type of equipment usually consists of either plate heat exchangers or tubular heat exchangers used for different stages of sterilization process. Tubular heating systems are advantageous than plate heating systems as a fouling layer on the heated surface has much less proportional effect on the area available for the product flow. Tubular systems can withstand a higher internal product pressures because of the absence of gaskets. This paper describes the computer aided design procedure for a tubular indirect type UHT heat exchanger for heating milk to sterilizing temperature. The unit consists of a triple tube heat exchanger (TTHE) with three concentric tubes having inner diameters 12.5, 22.5, 28.0 mm and outer diameters 15.0, 25.5, 31.0 mm respectively. The iterative computer aided design procedure gave an optimum length of 2.4 m for the TTHE with a milk processing capacity of 7.9 litres/ min. The overall heat transfer coefficients based on outside area of inner tube and inside area of middle tube for the TTHE were found to be 2564 and 2700 w/m^2 k respectively. The milk side heat transfer coefficient was found to be 4630 w/m^2 k.

Key words : Design, Heat Exchanger, Sterilization.

Ultra High Temperature (UHT) sterilization is a process of heating, in which the product is heated to a temperature of 135-150^{o}C in continuous flow in a heat exchanger and held at that temperature for a sufficient length of time to produce a satisfactory level of commercial sterility with an acceptable amount of change in the product (Burton, 1988). UHT treatment of milk gives product of better bacteriological and organoleptical qualities (Mehta, 1980). For continuous bulk processing by UHT method, either direct steam injection heating or indirect heating method is used. Direct heating equipment are relatively complex and requires special fabrication unlike heat exchanger plates and tubes. Compared to direct type, the indirect type of equipment is simple and can be effectively used with regeneration in different stages of UHT processing, using either plate heat exchangers (PHE's) or tubular heat exchangers (Burton, 1988). With any tubular heating system, a fouling layer on the heated surface has much less proportional effect on the total area available for the product flow unlike the PHE's in which the gap for the flow ranges between 3 to 6 mm. Tubular systems can withstand high internal pressures because of the absence of gaskets. Tubular heat exchangers of two concentric tubes will offer only a small surface area of heat transfer resulting in a large length of tube for the required temperature rise. Therefore, the total residence time will be unduly long. Hence triple tube heat exchanger (TTHE) in which the heat transfer takes place across two surfaces, is mostly used. Product flows through the middle annular passage and the heating fluid flows through the other two passages, so that the product is heated more rapidly because of the large heat transfer area. This paper describes the computer aided design procedure for TTHE for heating the milk to sterilizing temperature.

Design Considerations

Design of the TTHE involves calculating the length of the heat exchanger after selecting the tube diameters and volume flow rate of milk. The processing parameters like inlet, outlet temperatures of milk, steam temperature and properties like density, viscosity, specific heat and thermal conductivity of milk at various temperatures are taken into account for consideration. Properties of milk at higher temperature are obtained by fitting equations for the data given by Kessler (1981). Some of the available semi empirical models have length and surface temperature of the wall as variables in them. Length and wall temperatures on the tube surface are initially assumed and iteratively verified till they are equal to the calculated values. A general computer software programme in turbo Pascal was developed incorporating the processing parameters and diameters of the tubular heat exchangers.

Milk side heat transfer coefficient

Milk side heat transfer coefficient (h_m) was calculated as per the equation, (Geankoplis, 1978)

$$h_m = \frac{Nn_u . k_1}{D_{eq}} \quad .....1.$$

Where,

h_m= Milk side heat transfer coefficient, w/m²k
k_1 = thermal conductivity of milk at bulk mean temperature, w/m.k.
D_{eq} = equivalent diameter for the flow of milk, m

$$= \frac{4.\text{ (cross sectional area of flow)}}{\text{Wetted perimeter}}$$

$$= Di_2 - Do_1$$

Di_2 = inner diameter of the middle tube, m
Di_1 = outer dia of the inner tube, m

Nusselts Number

To determine the Nusselt number (N_{nu}), semiempirical models given by McAdams (1954) were used.

Steam side heat transfer coefficients

Steam side heat transfer coefficients, hc1 and hc2 inside the surface of the inner tube and outside the surface of the middle tube respectively are determined using Kern's modified equation (Kern, 1950) for laminar flow of condensate i.e $2\Gamma/\mu_l < 1800$.

$$hc_1 = 0.815 \times \left[\frac{k_1^3\, \rho_1 (\rho_1 - \rho_v)\, h_{fg}.g}{\Pi.\ \mu_l\, D_i\, (Ts - Twall)}\right]^{0.25} \quad ......2.$$

$$hc_2 = 0.725 \times \left[\frac{k_1^3\, \rho^2{}_1 (\rho_1 - \rho_v)\, h_{fg}.g}{\mu_l\, D_o\, (Ts - Twall)}\right]^{0.25} \quad ......3.$$

Γ= mass flow rate of condensate per meter length of periphery of tube, kg sec.m^{-1}
ρ_l = density of condensate at mean film temperature Tf, kg/m³

$$Tf = Ts - ¾ (Ts-Twall)$$

ρ_v = density of vapour at mean film temperature Tf, kg/m³
g = acceleration due to gravity, m/s²
k_1 = thermal conductivity of condensate at Tf, w m.k^{-1}
hfg= latent heat of condensation, j kg^{-1}
μ_1 = viscosity of condensate at Tf, pa.s
Ts = steam condensation temperature, °C
Twall = wall temperature of inside/ outside surface of heat transfer tube, °C
D_i , D_o = inside and outside diameters of tubes, m

Overall heat transfer coefficients

Overall heat transfer coefficients, U_{o1} and U*i2* based on outside area of inner tube and inside area of middle tube respectively are determined by the following equations

$$U_{o1} = 1 / (D_{01} - D_{i1}).\ A_{01} / 2.Tkss.\ A1m1 + A_{01} / Ai1.hc_1 + 1/ h_m \quad ....4.$$

$$U_{i2} = 1 / (D_{02} - D_{i2}).\ A_{i2} / 2.Tkss.\ A1m2 + A_{i2} / Ao2.hc_2 + 1/ h_m \quad .....5.$$

Where,

Di1, Do1 = inside and outside diameters of inner tube, m
Di2, Do2 = inside and outside diameters of middle tube, m
A1m1 = logarithmic mean area of inner tube
A1m2 = logarithmic mean area of middle tube
Ai1, Ao1 = inside and outside heat transfer areas of inner tube, m²
Ai2, Ao2 = inside and outside heat transfer areas of middle tube, m²
Tkss = thermal conductivity of SS 304 = 15 w/m.k

Rate of heat transfer

Rate of heat transfer, q is calculated by

$$q = m.cp.(Tmout - Tmin)$$

$$= v.\ \rho.\ \Pi.\ (Di_2^2 - Di_1^2)\ cp.\ (Tmout - Tmin) / 4 \quad ....6$$

where, cp = specific heat of milk, j / kg.k
m = mass flow rate of milk, kg/s
v = velocity of milk, m/s
ρ = density of milk at bulk mean temperature, kg/m³
T min = inlet temperature of milk, °C
T mout = outlet temperature of milk, °C

The overall rate of heat transfer, q is also calculated by

$$q = (U_{o1} \cdot A01 + U_{i2} \cdot Ai2) \cdot LMTD \quad ....7.$$

Steam side wall temperature

It is calculated using the following equation.

$$Ts - Twall / 1/hc_1 = Twall\ Tbmt / x / Tkss + 1/h_m \quad .....8$$

Where,

x = thickness of the wall of the tube, m
Tbmt = bulk mean temperature of the milk, °C
Twall = wall surface temperature on steam side, °C
Similarly wall temperature on the milk side is also calculated.

MATERIAL AND METHODS

Steps in the design of the length of the TTHE are as follows

i) Assuming the length of the tube, wall temperature on the steam side, milk side and selecting diameters of the tubes and volume flow rate of milk, Reynold, Prandtle & Graetz numbers are calculated.

ii) Depending on the type of flow, Nusselt number and milk side heat transfer coefficient are calculated.

iii) Steam side heat transfer coefficients hc1 & hc2 are calculated using equations 2 & 3

iv) Overall heat transfer coefficients are calculated using equations 4 and 5.

v) Overall rate of heat transfer is also calculated using equation 6

vi) Overall rate of heat transfer is also calculated in terms of length using equation 7. Equations 6 & 7 are equated to determine the actual length of the sterilizer.

vii) Temperature of wall surface on milk side and steam side are calculated using equation 8.

viii) Calculated length and wall surface temperatures are compared with the assumed values and process is repeated till the calculated values are almost equal to the assumedas values.

ix) Heat losses are calculated for correcting the length of the TTHE

Flow chart for the algorithm as shown in fig.1 was used to aid in the above design.

RESULTS AND DISCUSSION

General software was developed for design of an UHT heat exchanger for heating milk. It could be used to calculate the length of heating section for indirect type sterilization plant, when the diameters of the tubes, processing conditions and capacity of the system are known.

It is interesting to observe one specific case of designing UHT heating section having three concentric of tubes of inner diameters and outer diameters 12.5,22.5,28.0 mm and outer diameters 15.0,25.5,31.0 mm respectively. Annular clearance between the inner and middle tubes, for the flow of milk is 3.75 mm. Design trials were made with the help of general software programme, varying volume flow rate of milk from 1 lit/min to 15 lit/min with an increment of 1 lit/min. The variations in length with varying volume flow rates is shown in fig.2. It is evident from the plot, that for the given diameter of the tubes and required processing temperature, length attains a minimum value when flow behaviour changes from transition to turbulance. The minimum length obtained corresponding to a Reynolds number of 10,031 and a volume flow rate of 7.9 lit/min is 2.4 m. The output data obtained for the above specific case under the selected processing conditions is shown in table.1.

The optimum length of 2.4 m was found to be suitable for developing a laboratory model UHT sterilizer for heating milk from 85°C to 135° C assuming that milk is available at 85°C from preheater. This type of heating section having processing capacity of 7.9 lit/min will be useful for studying UHT sterilization process, fouling kinetics etc. in laboratory.

CONCLUSION

The computer software developed gives the length of the heating section for indirect type of tubular UHT sterilizer having selected diameters of the tubes, when the processing conditions and capacity of milk are known.

It can be concluded that an indirect type tubular heating section for a laboratory model UHT sterilizer can be designed with flow conditions in turbulent region, so that sterilization process, fouling kinetics etc., could be studied in the laboratory.

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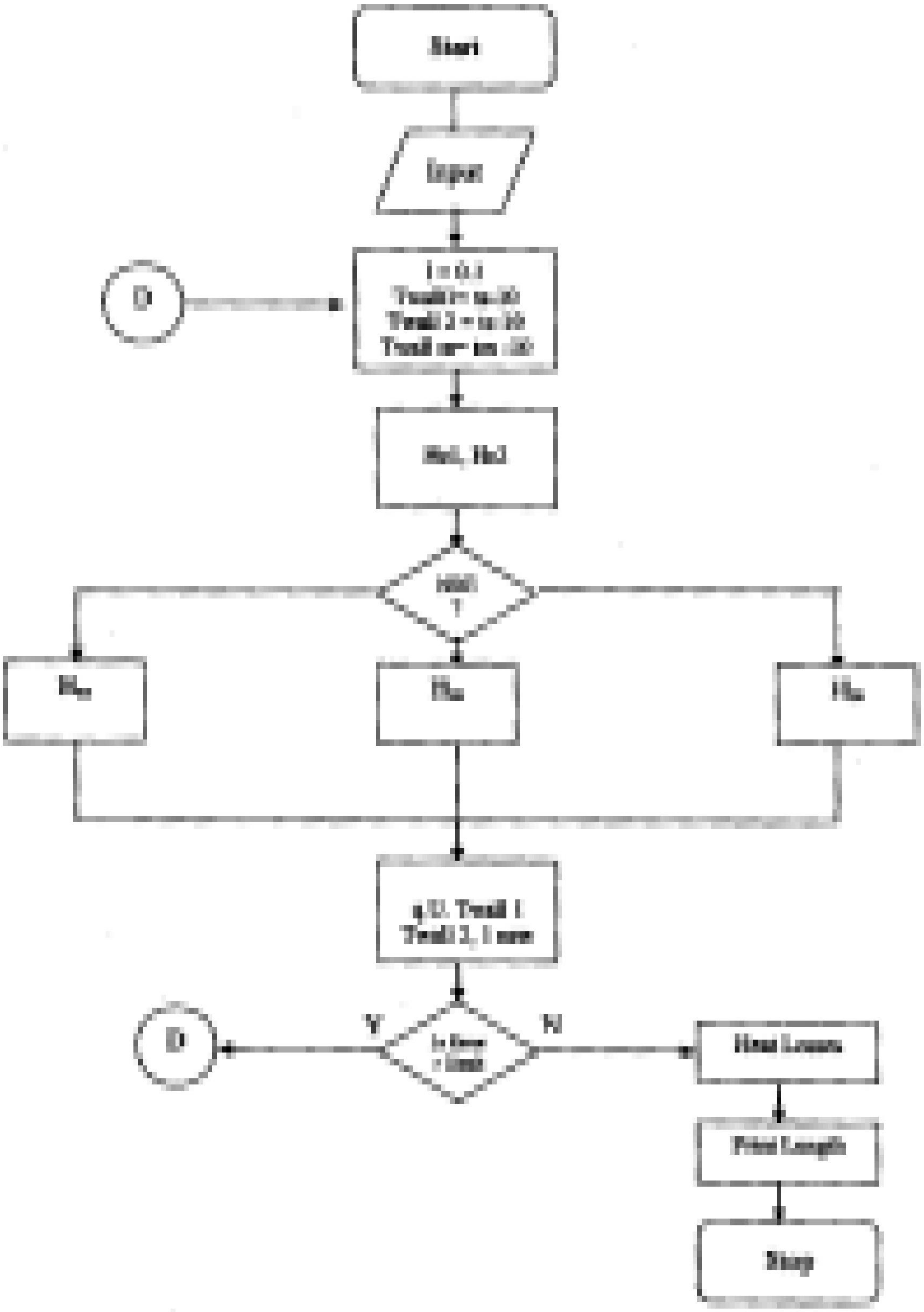

Fig.1 Flow chart of algorithm to design TTHE

Fig 2. Effect of volume flow rate on design length of TTHE

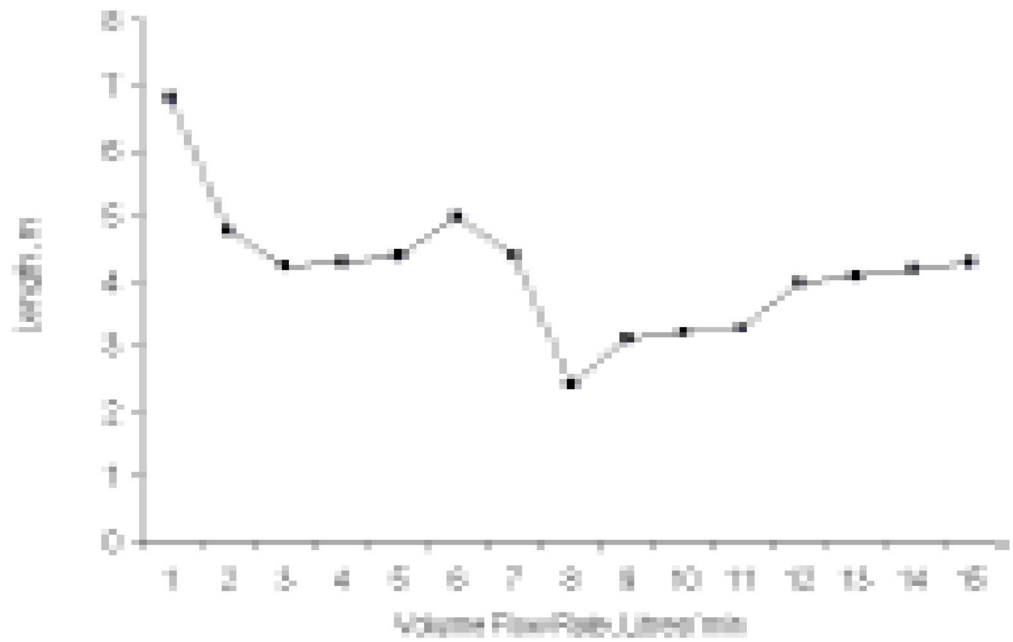

Table 1. Design output data for a typical UHT heat exchanger for a laboratory model sterilizer

DESIGN OF THE TRIPLE TUBE HEATING SECTION

NO. OF ITERATIONS = 11
STEAM SIDE HEAT TRANSFER COEFFICIENTS :
TEMPERATURE OF THE STEAM, °C = 150.00
TEMPERATURE OF WALL ON THE STEAM SIDE, °C = 142.68
INNER TUBE : HC1 = 14489.25 W/m².c
OUTER TUBE : HC2 = 14569.19 W/m².c
MILK SIDE HEAT TRANSFER COEFFICIENT:
CLEARANCE IN MM FOR FLOW OF MILK IN THE INNER ANNULUS : 3.750
TMILKIN = 85.00 °C TMILKOUT = 135.00 °C
RATE OF FLOW IN MILK IN LITRES/ MINUTE = 7.900
REYNOLDS NUMBER = 10030.95
INNER ANNULUS: HM = 4630.24 W/m².c
OVERALL HEAT TRANSFER COEFFICIENTS:
U01 = 2564.42 W/m².c. U12 = 2699.74 W/m².c
DIAMETERS OF THE TUBES IN MM
DI 1 = 12.50 D01 = 15.00
D12 = 22.50 D02 = 25.50
D13 = 28.00 D03 = 31.00
HEAT FLOW RATE = 25522.20 w
LENGTH OF HEATING SECTION IN METERS = 2.4

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