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Thermo Economically Optimum Heat Pump for Pasteurizing Milk

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Abstract: A thermo economic optimization analysis is presented yielding simple algebraic formula for estimating the optimum operating conditions of interconnected heat pump-refrigeration systems that are used in milk pasteurizing applications. The P_1-P_2 method is used in the present study, together with the thermal analyses of all system components, for thermo economic analysis of the system.

Key words: Thermoeconomics · Heat pump · Dairy · Milk pasteurizing · Optimization

INTRODUCTION

Optimization of the operating temperatures and the sizes of system elements for the combination of both heating and refrigeration applications in heat pump is extremely significant in order to get maximum earnings and yielding to minimum cost for these systems. There exist many parameters in optimizing heat pump and refrigerating systems as depicted in Fig. 1 in a thermo economical manner. Fixing and, so eliminating all these thermal and economical parameters, except the main operating temperature, T_2, depending on the certainty of operating characteristics of applications and the most efficient operating condition of the system, can determine optimum operating temperatures. The importance of energy saving application is increasing continuously and interconnected heat pump and refrigeration systems may be employed for this purpose with a similar idea to cogeneration systems. It is known that the performance of these types of systems is directly related to its operating temperatures and so the capacity of the system components together with its initial cost. A thermo economic feasibility study is necessary before installing the combination of heat pump-refrigeration systems. The basic topic of the present work depends upon this idea. A new thermo economic optimization technique is realized and presented for this purpose. An original formula is developed for calculating the optimum operating condition of the system at which minimum life cycle system cost occurs. A thorough search of the current literature showed that there were no previous studies on optimizing the heat pump-refrigeration for obtaining maximum thermo economic performance from these systems in detail. A practical method, the P_1-P_2 method, is used for optimizing the operating temperatures of heat pump-refrigeration system yielding to the best economy and original interesting results are presented. Variable parameters used in formulating the thermo economically optimum operating temperatures of the system are listed as technical life of the system, first cost of the systems elements per unit capacity or area, annual interest rate, present net price of energy and electricity, annual energy price rate, design temperature for the evaporator and the condenser of the system due to the design limitations, overall heat transfer coefficient of the evaporator, condensers and regenerative heat exchanger, design temperatures for milk pasteurizing and inlet-outlet milk temperatures, inlet-outlet cooling water temperatures ie. tower and basin temperatures for after condenser, mass flow rate and specific heat of milk, annual operating time, resale value and the ratio of annual maintenance and operation cost to the original cost. Additionally, optimum net cost of the system and optimal sizes or capacities of all system components together with additionally required water flow rate for after condenser are obtained algebraically in the present formulation method. Optimum operating temperature, T_2, can be calculated easily in a few minutes with the help of practical formulae. A thorough search of the present literature showed that there were several studies about the HPS performance and optimization [1-14]. All of these studies are not directly related to the present work. Original formulae are developed and presented finally.

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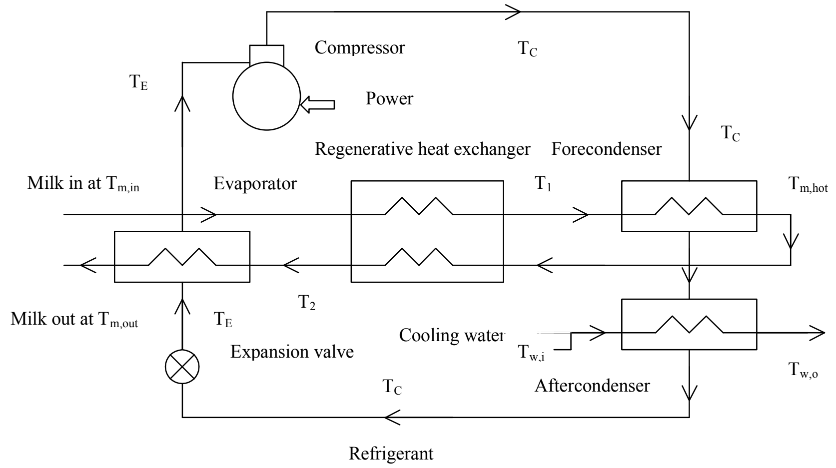

Fig. 1: Schematic Figure of Milk Pasteurizing System

Mathematical Formulation

Thermal Analyses: As a beginning, the amount of total required condenser capacity can be calculated as:

$$Q_{cond} = (COP+1).W_{comp} = Q_{FC} + Q_{AC} \tag{1}$$

COP is defined by the following approximated formula for liquid-to-liquid type heat pumps and the value of 0.75 drops up to 0.33 for air-to-air type heat pumps [15].

$$COP = 0.75.COP_C = 0.75.\frac{T_E}{(T_C - T_E)} \tag{2}$$

The heat rejection capacity of after condenser is evaluated by subtracting the capacity of fore condenser from the total condenser heat as follows.

$$Q_{AS} = (COP{+}1).W_{comp} - Q_{FC} \tag{3}$$

Amount of heat rejection from the after condenser can be calculated by Eqn. (4) also.

$$Q_{AC} = Q_E.\left(1+\frac{1}{COP}\right) - Q_{FC} \tag{4}$$

Since:

$$W_{comp} = \frac{Q_E}{COP} \tag{5}$$

The amount of cooling capacity of evaporator can be formulated as in the following form:

$$Q_E = (m.C_P)_{milk}.(T_2 - T_{m,out}) \tag{6}$$

The heat rejection capacity of fore condenser can be determined by the following equality.

$$Q_{FC} = (m.C_P)_{milk}.(T_2 - T_{m,in}) \tag{7}$$

Eqs. (3) through (7) are combined yielding to:

$$Q_{AC} = (m.C_P)_{milk}.(T_2 - T_{m,out}).\left(1+\frac{T_C - T_E}{0.75.T_E}\right) - (m.C_P)_{milk}.(T_2 - T_{m,in}) \tag{8}$$

Heat transfer area of after condenser can be obtained by means of the following equation.

$$Q_{AC}=U_{AC}.A_{AC}.LMTD=U_{AC}.A_{AC}.\frac{(T_{w,o}-T_{w,i})}{\ln\left(\dfrac{T_C-T_{w,i}}{T_C-T_{w,o}}\right)}\Rightarrow A_{AC}=\frac{Q_{AC}.\ln\left(\dfrac{T_C-T_{w,i}}{T_C-T_{w,o}}\right)}{U_{AC}.\Delta T_w} \tag{9}$$

Eqn. (9) may be written more explicitly as:

$$A_{AC}=\frac{(m.C_P)_{milk}}{U_{AC}.\Delta T_w}.\ln\left(\frac{T_C-T_{w,i}}{T_C-T_{w,o}}\right).\left\{(T_2-T_{m,out}).\left[1+\frac{T_C-T_E}{0.75.T_E}\right]-(T_2-T_{m,in})\right\} \tag{10}$$

The help of the following effectiveness and number of transfer unit relation can calculate heat transfer area of fore condenser.

$$\varepsilon_{FC}=1-e^{-NTU}=1-e^{-\frac{U_{FC}.A_{FC}}{(m.C_P)_{milk}}}\Rightarrow A_{FC}=\frac{-(m.C_P)_{milk}}{U_{FC}}.\ln(1-\varepsilon_{FC}) \tag{11}$$

Effectiveness of fore condenser can be formulated alternatively as in the Eqn. (12) to insert it into previous equation.

$$\varepsilon_{FC}=\frac{T_{m,hot}-T_1}{T_C-T_1}\Rightarrow 1-\varepsilon_{FC}=1-\frac{T_{m,hot}-T_1}{T_C-T_1}=\frac{T_C-T_{m,hot}}{T_C-T_1} \tag{12}$$

The heat balance equation around the regenerative heat exchanger yields.

$$T_{m,hot}-T_1=T_2-T_{m,in}\Rightarrow T_1=T_{m,hot}+T_{m,in}-T_2 \tag{13}$$

Eqn. (11) can be oriented to form Eqn. (14) by using Eqns. (12) and (13).

$$A_{FC}=\frac{-(m.C_P)_{milk}}{U_{FC}}.\ln\left(\frac{T_C-T_{m,hot}}{T_C-T_1}\right)=\frac{(m.C_P)_{milk}}{U_{FC}}.\ln\left(\frac{T_C-T_{m,hot}-T_{m,in}+T_2}{T_C-T_{m,hot}}\right) \tag{14}$$

The area of heat transfer for evaporator can be obtained in a same manner as follows.

$$A_E=\frac{-(m.C_P)_{milk}}{U_E}.\ln\left(1-\frac{T_2-T_{m,out}}{T_2-T_E}\right)=\frac{(m.C_P)_{milk}}{U_E}.\ln\left(\frac{T_2-T_E}{T_{m,out}-T_E}\right) \tag{15}$$

The effectiveness of the regenerative heat exchanger can be determined by Eqn. (16) for equal heat capacity rates in counter current heat exchangers as:

$$\varepsilon_{HX}=\frac{NTU}{1+NTU}\Rightarrow NTU=\frac{\varepsilon_{HX}}{1-\varepsilon_{HX}}\Leftrightarrow \varepsilon_{HX}=\frac{T_{m,hot}-T_2}{T_{m,hot}-T_{m,in}} \tag{16}$$

Area of heat transfer can be evaluated from the number of transfer units relation as:

$$NTU=\frac{U_{HX}.A_{HX}}{(m.C_P)_{milk}}=\frac{\varepsilon_{HX}}{1-\varepsilon_{HX}}\Rightarrow A_{HX}=\frac{(m.C_P)_{milk}}{U_{HX}}.\frac{(T_{m,hot}-T_2)}{(T_2-T_{\min})} \tag{17}$$

Economical Analysis: Initial cost of the compressor is evaluated by using the cost data [15,16] for heat pump compressors.

$$IC_{comp}=C_Q.W_{comp}=\frac{C_Q.Q_E}{COP}=\frac{C_Q.(m.C_P)_{milk}.(T_2-T_{m,out}).(T_C-T_E)}{0.75.T_E} \tag{18}$$

Life cycle operating cost of the compressor is determined as:

$$OC_{comp} = P_1.C_{EL}.W_{comp}.H = P_1.C_{EL}.H.\frac{Q_E}{COP} \tag{19}$$

Eqn. (19) can be rewritten more explicitly as follows.

$$OC_{comp} = P_1.C_{EL}.H.\frac{(m.C_P)_{milk}.(T_2 - T_{m,out}).(T_C - T_E)}{0.75.T_E} \tag{20}$$

Initial cost of evaporator is determined by the following.

$$IC_E = P_2.C_E.A_E = \frac{P_2.C_E.(m.C_P)_{milk}}{U_E}.\ln\left(\frac{T_2 - T_E}{T_{m,out} - T_E}\right) \tag{21}$$

Initial costs of fore condenser, after condenser and regenerative heat exchanger are calculated similarly as in the following relations.

$$IC_{FC} = P_2.C_{FC}.A_{FC} = \frac{P_2.C_{FC}.(m.C_P)_{milk}}{U_{FC}}.\ln\left(\frac{T_2 + T_C - T_{m,in} - T_{m,hot}}{T_C - T_{m,hot}}\right) \tag{22}$$

$$IC_{AC} = \frac{P_2.C_{AC}.(m.C_P)_{milk}}{U_{AC}.\Delta T_w}.\ln\left(\frac{T_C - T_{w,i}}{T_C - T_{w,o}}\right).\left\{(T_2 - T_{m,out}).\left[1 + \frac{T_C - T_E}{0.75.T_E}\right] - (T_2 - T_{m,in})\right\} \tag{23}$$

$$IC_{HX} = P_2.C_{HX}.A_{HX} = \frac{P_2.C_{HX}.(m.C_P)_{milk}}{U_{HX}}.\left(\frac{T_{m,hot} - T_2}{T_2 - T_{m,in}}\right) \tag{24}$$

Finally, the total cost of the system can be formulated as in the following equality.

$$TC = IC_{comp} + OC_{comp} + IC_E + IC_{FC} + IC_{HX} + IC_{AC} \tag{25}$$

and more explicit form as:

$$TC = A.(T_2 - T_{m,out}) + B.(T_2 - T_{m,out}) + C.\ln\left(\frac{T_2 - T_E}{T_{m,out} - T_E}\right) + D.\ln\left(\frac{T_2 + T_C - T_{m,in} - T_{m,hot}}{T_C - T_{m,hot}}\right) + E.\frac{(T_{m,hot} - T_2)}{(T_2 - T_{m,in})} + F.\left\{(T_2 - T_{m,out}).\left(1 + \frac{T_C - T_E}{0.75.T_E}\right) - (T_2 - T_{m,in})\right\} \tag{26}$$

where:

$$A = \frac{C_Q.(m.C_P)_{milk}.(T_C - T_E)}{0.75.T_E} \tag{27}$$

$$B = P_1.C_{EL}.H.\frac{(m.C_P)_{milk}.(T_C - T_E)}{0.75.T_E} \tag{28}$$

$$C = \frac{P_2.C_E.(m.C_P)_{milk}}{U_E} \tag{29}$$

$$D = \frac{P_2.C_{FC}.(m.C_P)_{milk}}{U_{FC}} \tag{30}$$

$$E = \frac{P_2.C_{HX}.(m.C_P)_{milk}}{U_{HX}} \tag{31}$$

$$F = \frac{P_2.C_{AC}.(m.C_P)_{milk}}{U_{AC}.\Delta T_w}.\ln\left(\frac{T_C - T_{w,i}}{T_C - T_{w,o}}\right) \tag{32}$$

Optimum value of T_2 can be calculated by deriving Eqn. (26) wrt. T_2 and setting it into zero algebraically.

$$\frac{\partial(TC)}{\partial(T_2)} = A. + B + \left(\frac{C}{T_2 - T_E}\right) + \left(\frac{D}{T_2 + T_C - T_{m,in} - T_{m,hot}}\right) - \frac{E.(T_{m,hot} - T_{m,in})}{(T_2 - T_{m,in})^2} + \left[\frac{F.(T_C - T_E)}{0.75.T_E}\right] = 0 \tag{33}$$

Eqn. (33) yields:

$$A. + B + \left(\frac{C}{T_{2,opt} - T_E}\right) + \left(\frac{D}{T_{2,opt} + T_C - T_{m,in} - T_{m,hot}}\right) + \left[\frac{F.(T_C - T_E)}{0.75.T_E}\right] = \frac{E.(T_{m,hot} - T_{m,in})}{(T_{2,opt} - T_{m,in})^2} \tag{34}$$

The second derivative of the overall cost function with respect to T_2, ($\partial^2 TC/\partial T_2^2$), is calculated by using this specific optimum T_2 value in this second derivative and result is found to be positive as illustrated in Eq. (9), which indicates a local minimum point.

$$\frac{\partial^2(TC)}{\partial(T_2)^2} = \left(\frac{-C}{(T_2 - T_E)^2}\right) - \left(\frac{D}{(T_2 + T_C - T_{m,in} - T_{m,hot})^2}\right) + 2.E.\frac{(T_{m,hot} - T_{m,in})}{(T_2 - T_{m,in})^3} \geq 0 \tag{35}$$

The economical parameter P_1 [17] is defined by the following formula for i = d case:

$$P_1 = \frac{N}{1+i} \tag{36}$$

and for i # d:

$$P_1 = \frac{1}{(d-i)}.\left\{1 - \left[\frac{1+i}{1+d}\right]^N\right\} \tag{37}$$

with the economical parameter P_2 [17]

$$P_2 = 1 + P_1.M_S - R_V.(1+d)^{-N} \tag{38}$$

RESULTS AND DISCUSSION

For a typical milk pasteurizing optimization problem, it is assumed that $U_{HX} = 0.5$ kW/(m^2.K), $U_E = U_{FC} = U_{AC} = 0.6$ kW/(m^2.K), $T_E = 270.15$ K, $T_C = 353.15$ K, $T_{m,hot} = 346.15$ K, $T_{m,in} = 280.15$ K, $T_{m,out} = 277.15$ K, i = d = 0.09, $C_{EL} = 0.035$ \$/(kW.hr), $C_{FC} = C_{AC} = C_{HX} = C_E = 95$ \$/m^2, H = 1440 hr/year, N = 6 years, $C_Q = 120$ \$/kW, $(m.C_P)_{milk} = 15$ kW/K, $M_s = 0$, $R_v = 0$. The optimum T_2 value for the milk pasteurizing system is calculated by using Eq. (34) as 288.495 degrees K. The values of overall life cycle costs are plotted in Fig. 2 and presented in Table 1 also. It can be deduced that there exists a local minimum value for milk pasteurizing applications. Neither excessive nor deficient values of T_2 of the system will be cost effective other than the optimum T_2.

Table 1: Net overall life cycle costs versus temperature T_2.

T_2(C)	10	15.435	20	25	30	35	40
TC (US \$)	75759	49938	54064	62975	73522	84803	96470

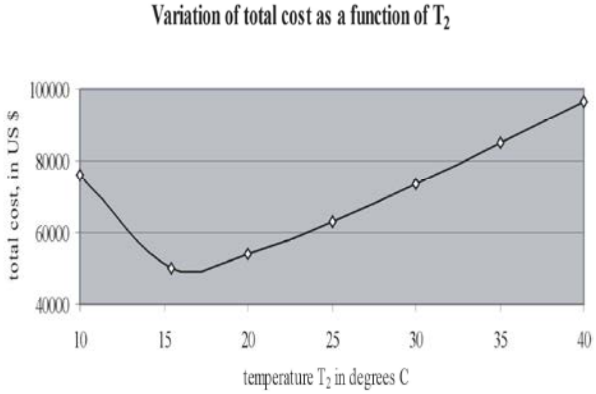

Fig. 2: Overall Life Cycle Costs versus Temperature T_2

It is clear that there exist good thermal performance at this optimum point for the system. The optimal sizes of system components corresponding to optimal T_2 value are introduced in Table 2.

Summary: The optimum operating temperatures and sizes of all system components are calculated at which minimum life cycle cost occurs for a typical the milk pasteurizing heat pump system. The validity of the optimization formulation is checked. These systems must be designed close to this optimum point. The present formulae may seem to be helpful for the designers and manufacturers of these systems.

Table 2: Optimal operating conditions for the system components

T_1 (C)	A_{HX} (m^2)	A_E (m^2)	A_{AC} (m^2)	A_{FC} (m^2)	W_{comp} (kW)	ε_{FC}	ε_{AC}	ε_E	ε_{HX}	$(mC_P)_w$ kW/K
64.565	204.74	24.21	4.055	19.768	70.3	0.5465	0.1	0.62	0.8722	23.092

Nomenclature

A	Fixed parameter defined as in Eq. (27),
A_{AC}	Area of heat transfer surface of the after condenser, (m^2)
A_E	Area of heat transfer surface of the evaporator, (m^2)
A_{FC}	Area of heat transfer surface of the fore condenser, (m^2)
A_{HX}	Area of heat transfer surface of the regenerative heat exchanger, (m^2)
B	Fixed parameter defined as in Eq. (28),
C	Fixed parameter defined as in Eq. (29),
C_{AC}	Area dependent first cost of the heat exchanger, ($\$/m^2$)
C_E	Area dependent first cost of the evaporator, ($\$/m^2$)
C_{FC}	Area dependent first cost of the fore condenser, ($\$/m^2$)
C_{HX}	Area dependent first cost of the regenerative heat exchanger, ($\$/m^2$)
C_{EL}	Cost of electricity, [$/(kW.hr)]
C_Q	Capacity dependent first cost of the heat pump system, ($/kW)
COP	Coefficient of performance of the heat pump based on evaporator capacity,
COP_C	Coefficient of performance of the Carnot cycle heat pump,
D	Fixed parameter defined as in Eq. (30),
d	Market discount rate in fraction,
E	Fixed parameter defined as in Eq. (31),
F	Fixed parameter defined as in Eq. (32),
H	Annual time of operation, (h/yr)
i	Energy price rate in fraction,
IC_{AC}	Initial cost of the after condenser, ($)
IC_{comp}	Initial cost of the compressor, ($)
IC_E	Initial cost of the evaporator, ($)
IC_{FC}	Initial cost of the fore condenser, ($)
IC_{HX}	Initial cost of the regenerative heat exchanger, ($)
LMTD	Logarithmic mean temperature difference,
$(mC_P)_{milk}$	Capacity rate of milk, (kW/K)
$(mC_P)_w$	Capacity rate of water flowing through the after condenser, (kW/K)
M_S	Ratio of annual maintenance and operation cost into first original cost,
N	Technical life of the cascade refrigerating system, (yr)
NTU	Number of transfer units,
OC_{comp}	Life cycle operation cost of the compressor, ($)
P_1	Ratio of the life cycle energy cost or savings to that for the first year, (yr)
P_2	Ratio of the life cycle expenditures incurred because of the additional capital investment to the initial investment,
Q_{AC}	Heat load of after condenser, (W)
Q_{cond}	Overall heat load of two condensers, (W)
Q_E	Cooling capacity of evaporator, (W)
Q_{FC}	Heat load of fore condenser, (W)
R_v	Ratio of resale value to the first original cost,
TC	Total cost of the system, ($)
T_C	Condensing temperature, (K)
T_E	Design temperature of evaporator due to milk outlet temperature, (K)
$T_{m,in}$	Inlet temperature of milk, (K)
$T_{m,out}$	Design outlet temperature of milk, (K)
$T_{m,hot}$	Design pasteurizing temperature of heated milk, (K)
$T_{w,i}$	Inlet temperature of cooling water entering after condenser, (K)
$T_{w,o}$	Outlet temperature of cooling water leaving after condenser, (K)
T_1	Temperature of milk leaving entering fore condenser, (K)
T_2	Temperature of milk entering evaporator, (K)
$T_{2,opt}$	Optimum temperature of milk entering evaporator, (K)
U_{AC}	Overall heat transfer coefficient of the after condenser, [$kW/(m^2.K)$]
U_E	Overall heat transfer coefficient of the evaporator, [$kW/(m^2.K)$]
U_{FC}	Overall heat transfer coefficient of the fore condenser, [$kW/(m^2.K)$]
U_{HX}	Overall heat transfer coefficient of the regenerative heat exchanger, [$kW/(m^2.K)$]
W_{comp}	Power input to the compressor, (kW)
ΔT_w	Inlet-exit temperature difference of cooling water flowing through the after condenser, (K),
ε_{FC}	Effectiveness of fore condenser,
ε_{HX}	Effectiveness of regenerative heat exchanger.

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