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Optimum heat pump in drying systems with waste heat recovery

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Abstract

A thermo economic optimization analysis is presented yielding simple algebraic formula for estimating the optimum operating conditions of heat pump with auxiliary heating that are used in drying applications. A simple economic analysis method is used in the present study, together with the thermal analyses of all system components, for thermo economic analysis of the system.

Keywords: Thermo economics; Heat pump; Drying; Waste heat recovery; Optimization

1. Introduction

Optimization of the operating temperatures and the sizes of system elements for heat pump applications 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 systems with auxiliary heating in drying 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 temperatures, T_1, and T_3, 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 heat pump driers with waste heat recovering 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 initial and operating costs. A thermo economic feasibility study is necessary before installing the combination of heat pump driven drying systems including waste heat recovery. 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 systems for obtaining maximum thermo economic performance from these systems in detail. A practical method, the $P_1 - P_2$ method that was presented by Duffie and Beckman (1980, Chapter 11), is used for optimizing the operating temperatures of heat pump driers 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, required drier capacity, 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,

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Nomenclature

a	coefficient of polynomial equation, Eq. (38)
A	fixed parameter defined as in Eq. (26)
A_C	area of heat transfer surface of the condenser (m^2)
A_E	area of heat transfer surface of the evaporator (m^2)
A_{HX}	area of heat transfer surface of the regenerative heat exchanger (m^2)
b	coefficient of polynomial equation, Eq. (38)
B	fixed parameter defined as in Eq. (27)
b	coefficient of polynomial equation, Eq. (38)
c	coefficient of polynomial equation, Eq. (38)
C	fixed parameter defined as in Eq. (28)
C_C	area dependent first cost of the condenser ($/$m^2$)
C_D	capacity dependent first cost of the drier ($/kW)
C_E	area dependent first cost of the evaporator ($/$m^2$)
C_{EL}	cost of electricity [$/(kW h)]
C_{EN}	cost of energy used in auxiliary heater [$/(kW h)]
C_H	capacity dependent first cost of the auxiliary heater ($/kW)
C_{HX}	area dependent first cost of the regenerative heat exchanger ($/$m^2$)
C_P	specific heat of air [kJ/(kg K)]
C_Q	capacity dependent first cost of the heat pump system ($/kW)
COP	coefficient of performance of the heat pump based on evaporator capacity
COP_C	coefficient of performance of the equivalent Carnot refrigeration cycle
D	fixed parameter defined as in Eq. (29)
d	market discount rate in fraction
E	fixed parameter defined as in Eq. (30)
F	fixed parameter defined as in Eq. (31)
G	fixed parameter defined as in Eq. (32)
H	annual time of operation (h/year)
i	energy price rate in fraction
IC_C	initial cost of the condenser ($)
IC_{comp}	initial cost of the compressor ($)
IC_D	initial cost of the drier ($)
IC_E	initial cost of the evaporator ($)
IC_H	initial cost of the auxiliary heater ($)
IC_{HX}	initial cost of the regenerative heat exchanger ($)
K	fixed parameter defined as in Eq. (33)
m	mass flow rate of air (kg/s)
M_S	ratio of annual maintenance and operation cost into first original cost
N	technical life of the heat pump system (year)
NTU	number of transfer units
OC_{comp}	life cycle operation cost of the compressor ($)
OC_H	life cycle operation cost of the auxiliary heater ($)
P_1	ratio of the life cycle energy cost or savings to that for the first year (year)
P_2	ratio of the life cycle expenditures incurred because of the additional capital investment to the initial investment
Q_D	design sensible heating capacity of the drier (kW)
Q_E	cooling capacity of evaporator (kW)
Q_H	heating capacity of the auxiliary heater (kW)
R_V	ratio of resale value to the first original cost
TC	total cost of the system ($)
T_C	condensing temperature (K)
T_D	design temperature of inlet air when entering to drier (K)
T_E	design temperature of evaporator (K)
T_0	inlet temperature of ambient air (K)
T_1	temperature of air entering into auxiliary heater (K)
$T_{1,opt}$	optimum temperature of air entering into auxiliary heater (K)
T_2	temperature of air leaving the drier (K)
T_3	temperature of circulating air leaving the evaporator (K)
$T_{3,opt}$	optimum temperature of air leaving the evaporator (K)
T_4	temperature of circulating air entering the evaporator (K)
U_C	overall heat transfer coefficient of the condenser [kW/(m^2 K)]
U_E	overall heat transfer coefficient of the evaporator [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)
ε_E	effectiveness of the evaporator
ε_C	effectiveness of the condenser
ε_{HX}	effectiveness of the regenerative heat exchanger

design temperatures for drier together with ambient air and exhaust air temperatures, mass flow rate and specific heat of air, 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