Design of Nomogram to Predict Performance of Heat Pump Dryer

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Abstract: - In order to improve product quality, decrease capital cost and increase final cost of dried products, several studies have been conducted. Using heat pump dryers the latent and sensible heat of exhaust air from drying chamber are saved , therefore, the energy efficiency of systems have been increased. The results of performance and economic analysis of an air source heat pump assisted-drying system are presented and the relations between these are showed in a nomogram which designed to allow the approximate graphical computation of a function and to predict the system performance graphically for wide ranges of evaporator and condenser temperatures and different and make a connection between them and economic analysis.

Key-Words: Nomogram, Heat Pump, Dryer, Coefficient of Performance (COP), Evaporator Temperature, Compressor Work, Economic Payback Period.

1 Introduction

The main objective of any drying process is to produce a dried product of desired quality at minimum cost and maximum throughput and to optimise these factors consistently [1]. Drying is an energy intensive operation, therefore most researchers have been tried to find energy efficient systems and save energy in drying heat processes. In drying process the air leaving the dryer has almost the same enthalpy which it had on entering the system, hence a considerable part of the enthalpy used on drying can be regained by condensing the absorbed water vapour. Utilizing energy efficient heat pump in drying system can achieve this goal and recover both latent and sensible heat which would otherwise be wasted. One of the most efficient and controllable ways of drying moist materials is by using a heat pump drying. For years heat pumps have been known as an efficient method of energy recovery. Heat pump for drying is difference, of the hot heat produced by condenser and cold heat by the evaporator will be use concurrently during the operation. The heat from the condenser will produced hot and will use to heat the material and the cold heat from the evaporator will be use in dehumanization process. Their ability to convert the latent heat of vapour condensation into the sensible heat of an air stream passing through the condenser makes them attractive in drying applications especially when combined with the ability to produced well-controlled drying conditions [2]. For these reasons heat-pump drying has been used for decades in wood kilns to dehumidify air and lumber quality. Following the general trend to improve product quality and reduce energy consumption, many researcher have acknowledged the specific features of heat pumps, which has resulted in the rapid growth of both theoretical and applied research on heat pump drying (Table 1).

Table1. Some studies in heat-pump drying

Source	Location	Application (s)	Conclusions
(Theerakulpisut, 1990) [4]	Australia	Grain	An open cycle HPD performed better during the initial stage when the product drying rate is high.
(Meyer, and Greyvenstein, 1992) [5]	South Africa	Grains	The HPD is more economical than other dryers.
(Rossi et al.,1992) [6]	Brazil	Vegetable (Onion)	Better product quality and energy saving of the order of 30% was obtained.
(Mason and Blarcom, (1993) [7]	Australia	Macadamia nuts	---
(Strommen and Kramer 1994) [8]	Norway	Marine products (fish)	The high quality of the dried products was Highlighted as the major advantage of HPD.
(Prasertsan et al., 1997); (Prasertsan and Saen-saby, 1998)[9-10]	Thailand	Agricultural food drying (bananas)	HPD is economically feasible and for drying high moisture materials is so appropriate.
(O'Neill et al., 1998) [11]	New Zealand	Apples	Modified atmosphere heat pump (New Zealand) heat pump system drying (MAHPD) produces products with a high level of open pore structure, contributing to the unique physical properties
(Strommen et al. 1999) [12]	---	---	HPD with hydrocarbon and natural working fluids can save significant amounts of energy. With comparison the performance of several refrigerants, they found that ammonia was the most favourable refrigerant in the temperatures: 30-80°C.
(Chou et al., 1998, 2001);(Chua et al., 2000) [13,14,15]	Singapore	Agricultural and marine products	With scheduled drying conditions the quality of products can be improved
(Oktay et al., 2003) [16]	Turkey	Wool	The SMER was between 0.65-1.75 kg/kWh. COP was between 2.47-3.95.
(Teeboonma et al.,2003) [17]	Thailand	Fruits (papaya and mango glace)	Mathematical models of fruits drying using HPD are developed and validated experimentally. The optimum criterion is minimum annual total cost per unit of evaporating-water. The effects of initial moisture content, cubic size and effective diffusion coefficient of products on the optimum conditions of HPD are also investigated. exergy and energy analysis was made.
(Kohayakawa et al., 2004) [18]	Brasil	Mango	The energy efficiency improved compared with an electrical resistance dryer.
(Hawlader et al., 2006) [19]	Singapore	Apple, guava and potato	Modified atmosphere heat pump dryer produced better physical properties.
(Chegini et al., 2007) [20]	Iran	Plum	The optimum temperature of drying for plums is in vicinity of 70-80ºC; also (SMER) of designed dryer was notably more than conventional types of dryers in respect to saving the energy
(Phoungchandang et al., 2009) [21]	Thailand	Garlic and White mulberry	Computer simulation model of the heat pump dehumidified drying shown to be in good agreement with experimental results.
(Aktaş et al., 2009) [22]	Turkey	apples	A system which is composed of the combination of both dryers is considered to be more efficient

The key advantages and limitations of heat pump dryers are as follows [3]:

Advantages:

- Higher energy efficiency with controlled temperature profile to meet product requirements
- Better product quality with control temperature profile to meet product requirements
- A wide range of drying conditions typically from -20ºC to 100ºC (with auxiliary heating) is feasible
- Consistent output of products
- Excellent control of the environment for high value products and reduced electrical consumption for low- valued products
- Suitable for both high-value and low-value products
- Aseptic processing is possible.

Limitations:

- Auxiliary heating may be required for high-temperature drying due to the critical pressure level of some refrigerants
- Initial capital cost may be high de to many refrigerant components. Requires a steady state period for system to attain desired drying conditions.
- Required regular maintenance of components
- Leakage of refrigerant to the environment if cracking of pipes occurs due to pressurized systems

2 Mathematical Modeling

Figure 1 shows the heat pump dryer system and Figure 2 Represents the schematic diagram of this system. The system consists of two heat exchangers as condenser and evaporator, a thermostatic expansion valve a compressor, drying chamber, supporting structure and casing. The heat pump system and the chamber are attached together so that it becomes one unit. The heat from the condenser will produced hot and will use to heat the material in chambers and the cold heat from the evaporator will be use in dehumanization process.

Fig.1. Heat pump dryer

2.1 Theoretical performance Analysis of heat pump drying system

In general, simulation can be used to study variations in system or component configurations in order to identify critical parameters [23].The starting point of a heat pump model is the description of the operation of a heat pump in terms of mathematical relationships.

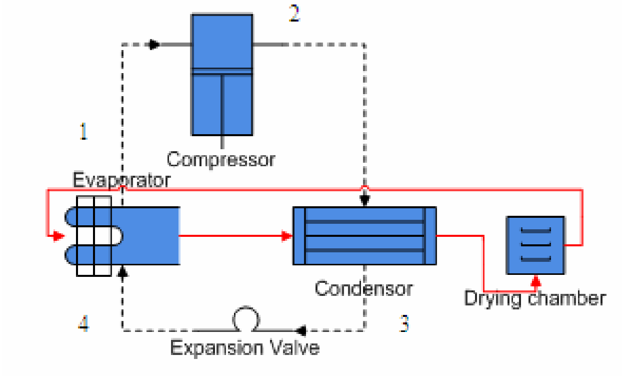


Fig.2. Schematic Diagram of heat pump dryer

The main parameters of the compressor are volumetric efficiency (η_{vol}), refrigerant mass flow rates (m_r) and compression power (W) [23].

$$\eta_{vol} = 1 - C\left[(CR)^{\frac{1}{n}} - 1\right] \quad (1)$$

$$m_r = V_{st} N_i \left({}^{1}\!/_{v_1} \right) \eta_{vol} \quad (2)$$

$$W = m_r (h_2 - h_1) \quad (3)$$

Applying the energy equation for a mass m of refrigerant in the evaporator yields:

$$Q_1 = m.(h_1 - h_4) \quad (4)$$

The heat rejection in the condenser is given by:

$$Q_{Cond} = Q_{De\sup erheating} + Q_{Condensetion} \quad (5)$$

For a mechanical vapor compression system, the net energy supplied is usually in the form of work, mechanical or electrical, and may include work to the compressor and fans or pumps. Thus, the coefficient of performance is:

$$COP = \frac{Q_{cond}}{W} \tag{6}$$

2.2 Thermodynamic properties of refrigerant

In order to obtain the performance of the conventional heat pump or SAHP working with R134a as working fluids, knowledge of the thermodynamic properties is required [24]. Such properties are published in tabular form for R134a [ASHRAE]. Using these data, a regression analysis has been carried out to correlate their thermodynamic properties from - 50°C to near the critical point of each refrigerant. The following correlations are obtained:

$$Ln(P_s) = A_0 + A_1T + A_2T^2 + A_3T^3 \tag{7}$$

$$Ln(\nu_{sv}) = B_0 + B_1T + B_2T^2 + B_3T^3 \tag{8}$$

$$h_{sl} = C_0 + C_1T + C_2T^2 \tag{9}$$

$$h_{SV} = D_0 + D_1T + D_2T^2 \tag{10}$$

$$S_{SV} = E_0 + {E_1}/{T} + {E_2}/{T^2} \tag{11}$$

$$h_{\sup} = \sum_{n=0}^{n=2} F_n.T^n + P.\sum_{n=3}^{n=5} F_n.T^{n-3} \tag{12}$$

$$S_{\sup} = \sum_{n=0}^{n=2} G_n.T^n + P.\sum_{n=3}^{n=5} G_n.T^{n-3} \tag{13}$$

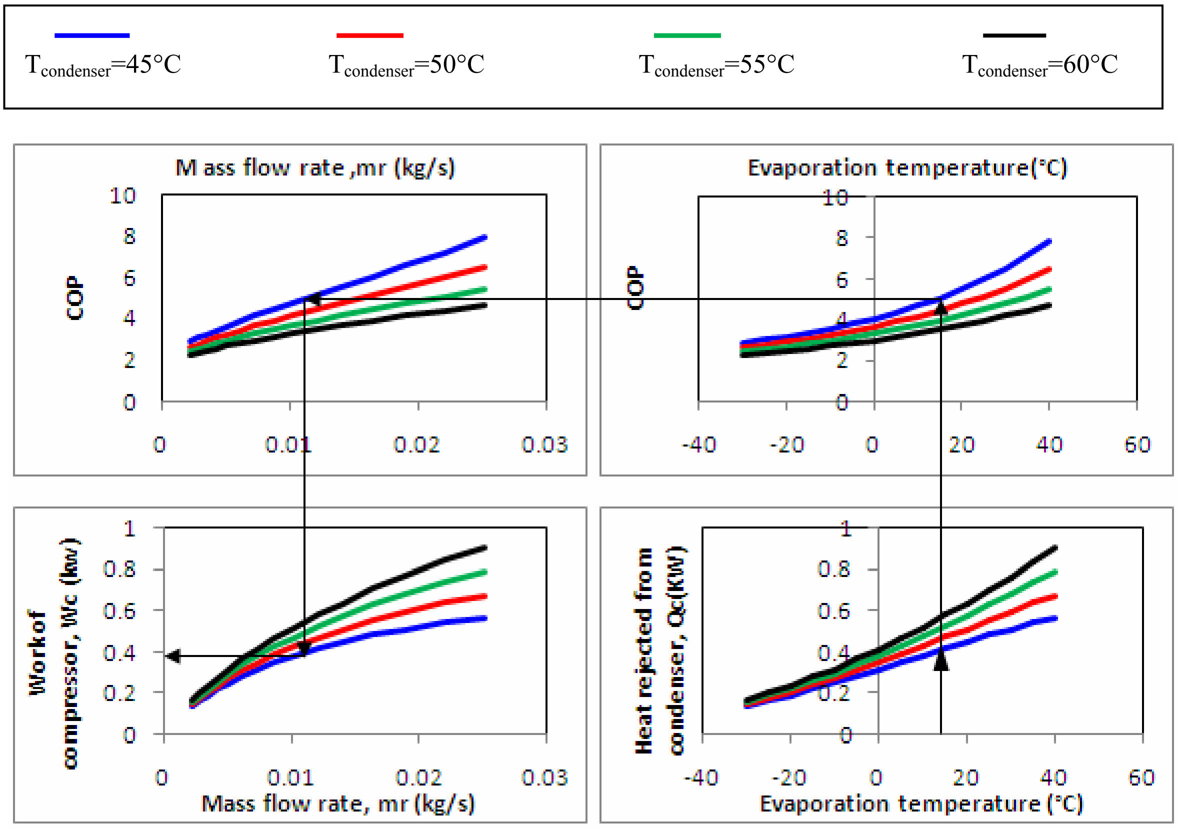
The numerical constants of the above correlations for working refrigerant R134a are given in Table 2.

Table2. Numerical coefficients for equations (24)-(30) - R134a

Coefficient		***R 134a***
P	A_0	-35.94481
	A_1	0.265213
	A_2	$-0.6782399*10^{-3}$
	A_3	$0.6323821*10^{-6}$
	CC	0.9920
	Percent of error	0.5332
v_{sv}	B_0	$0.1221149*10^{2}$
	B_1	$-0.7384953*10^{-1}$
	B_2	$0.7117396*10^{-4}$
	B_3	0
	CC	0.99982
	Percent of error	2.48206
h_{sl}	C_0	-6.702179
	C_1	0.1675422
	C_2	$0.2154294*10^{-2}$
	CC	0.99995
	Percent of error	0.205
h_{sv}	D_0	83.23572
	D_1	1.742258
	D_2	$- 0.2140479 * 10^{-2}$
	CC	0.99891
	Percent of error	0.19386
S_{sv}	E_0	1.69001
	E_1	-27.95583
	E_2	10543.32
	TR(°C)	- 50:80
	CC	0.9867
	Percent of error	0.184
h_{sup}	F_0	155.1313
	F_1	0.8471667
	F_2	$0.209139 * 10^{-3}$
	F_3	34.7401
	F_4	-0.3860322
	F_5	$0.672008 * 10^{-3}$
	CC	0.99586
	Percent of error	0.28568
s_{sup}	G_0	1.100179
	G_1	$0.297224 * 10^{-2}$
	G_2	$- 0.166979 * 10^{-5}$
	G_3	- 1.479631
	G_4	$0.67361 * 10^{-5}$
	G_5	$-0.79838 * 10^{-5}$
	TR(°C)	30:90
	PR	0.6:3
	CC	0.99034
	Percent of error	0.2326187

3. Design of Nomogram

Operating conditions such as evaporator temperatures and condenser temperatures have been considered as important factors which affect performance system. In order to show the effect of evaporator temperature on the performance of the heat pump while the other operating parameters are kept constant and also the effect of mass flow rate on the performance of system a nomogram has been designed (Fig.3). Based on a range of evaporator temperatures, from this nomogram, the performance characteristics of system can be obtained immediately.



4 Results and discussion

The variation of the heat rejected from condenser and the coefficient of performance against evaporator temperature present in nomogram. It is observed that the condenser heat load increases as evaporation temperature rises. Due to the rise in heat rejected from condenser, the COP increases with evaporation temperature.

The effect of mass flow rate on COP and compressor work is depicted in nomogram. The COP and W increases with mass flow rate, this is due to the increase in evaporation temperature with mass flow rate. As mass flow rate rises the volumetric efficiency increases and the decrease in Specific volume, when the influence of refrigerant mass flow rate is more declared than that of the (h_2-h_1), W increases with evaporation temperature.

Variations of the condenser temperatures on the COP, heat rejected from condenser and work of compressor are shown in this nomogram. Condenser heat load and compressor work increase as the condenser temperature go up, but COP decline with increasing of condenser temperature.

6 Conclusion

A parametric study has been conducted to analyze the effects of different variables on the performance of the system. In order to show the effect of operating conditions on the performance of system a nomogram has been designed. Using this nomogram, based on a range of evaporator temperatures, the performance characteristics of system (Coefficient of Performance (COP), amount of heat rejected from condenser and compressor work) can be obtained immediately for a wide range of condenser temperatures.

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Nomenclature

A_{0-3}	Numerical constant in equation (7)
B_{0-3}	Numerical constant in equation (8)
C_{0-3}	Numerical constant in equation (9)
D_{0-3}	Numerical constant in equation (10)
E_{0-3}	Numerical constant in equation (11)
F_{0-3}	Numerical constant in equation (12)
G_{0-3}	Numerical constant in equation (13)
C	Clearance Percentage
COP	Coefficient of Performance
CR	Compression Ratio

h	Specific enthalpy, KJ/Kg
m	Mass flow rate, Kg/s
Q	Rate of heat transfer, kw
T	Temperature,K
ν	Specific volume, m^3/kg
V	Displacement volume, m^3
W	Work

Greek letters

η	Efficiency

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