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ALGORITHM FOR CALCULATING DESIGN PARAMETERS OF BATCH TYPE HEAT PUMP DRYER

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ABSTRACT Heat pump-assisted drying is a highly efficient and easily controllable system to obtain accurate drying conditions for agricultural products. A heat pump dryer's mathematical models consist of three sub-models, namely drying models, heat pump models, and performance models. The research objective was to develop an algorithm for calculating design parameters for batch-type, closed-loop heat pump dryers. Python programming language was used to code algorithms for heat and mass balance of the HP dryer's refrigerant and air cycle under constant drying rate conditions. Inlet drying air conditions, drying material properties, and drying time were inputs to the algorithm. The power requirement of compressor, condenser and evaporator, specific moisture extraction rate, moisture extraction rate, and coefficient of performance were calculated. These heat pump dryer design parameters can be used in fabricating batch-type heat pump dryers.

Keywords: Drying, Heat pump, SMER

INTRODUCTION Food drying is one of the strategies for food preservation and is commonly used in the food industry. Drying is an energy-intensive process and a widely used in many industries, including food, chemical, and process industries. Simultaneous heat and mass transfer processes occur in the drying process, and it is a complex process. Several dryer types are used for drying food, such as solar dryers, fluidized bed dryers, spray dryers, freeze dryers, vacuum dryers, pneumatic dryers, and heat pump dryers.

In conventional dryers, the exhaust air is released into the atmosphere, and losses of energy taking place, reducing the performance, resulting in low specific moisture extraction rate SMER (about 0.2–0.6 kg/kWh) (Yamankaradeniz et al., 2016). The heat pump dryers use this energy in the exhaust air as both the latent heat and sensible heat improve the overall thermal performance of the dryer. Further, the condensation at the evaporator reduces the humidity of the working air, increasing the effectiveness of the product drying.

The heat pump dryers SMER is in the range of 1.0–4.0 kg/kWh with an average of 2.0-2.5 kg/kWh (Hodgett, 1976; Jolly, 1990). The latent heat of water is equivalent to a SMER of 1.56 kg/kWh. A heat pump, by its name, is a device implicitly supplying heat mainly for space heating applications and heat recovery. Heat pump dryers are primarily consisting two components: a drying chamber and a heat pump unit. The heat pump unit includes an evaporator, condenser, expansion valve, and compressor. Comparing vegetable drying by the HPD and a conventional dryer using an electrical heater found that an energy saving of 40% can be made and the processing time reduced by 40.7% (Rossi et al., 1992).

Developing a dryer with optimum design parameters for food drying is complex due to the different physicochemical characteristics. Also, the drying rates of food products vary with time. Therefore, the objective of this research was to develop an algorithm to determine the optimum design parameters for batch-type, closed-loop heat pump drying.

MATERIALS AND METHODS

The schematic diagram of a heat pump dryer is illustrated in figure 1. The air flows through the drying chamber to gain moisture from the crop. This humid air is cooled down in the evaporator, recovered the heat, and extracts moisture from the air, completing a dehumidification process. The heat energy removes from the air by the refrigerant in the evaporator, and the refrigerant evaporates. A portion of air bypass the evaporator and directly goes through the condenser, and the total air amount that goes through the evaporator is feed to the condenser. The condenser released heat energy to the surroundings due to the condensation of the refrigerant. The dehumidified air gains this heat energy, and the heated air is directed to the drying chamber.

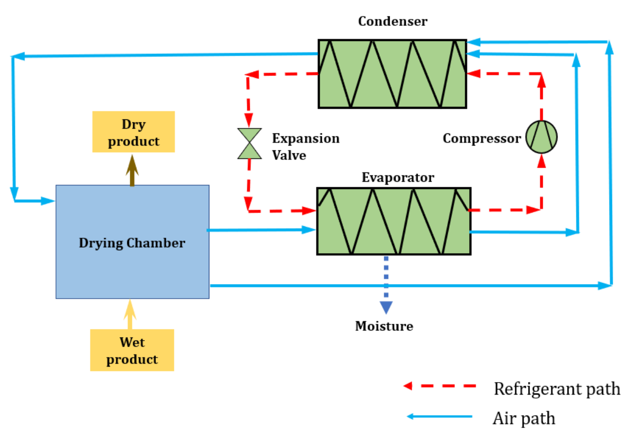

Figure 1. Schematic diagram of heat pump dryer.

A heat pump dryer's mathematical models consist of three sub-models: drying models, heat pump models, and performance models.

Drying model Simulations limited to constant rate drying conduct to avoid dynamic behavior of falling rate drying. This study considered a linear equilibrium model regarding thermal equilibrium between drying air and the crop. This model has been modified from the previous models (Achariyaviriya et al., 2000; Chou et al., 1994; Prasertsan et al., 1996; Teeboonma et al., 2003; Hossain et al., 2013; Pal & Khan, 2008). The energy and mass balance equation has expressed as equations 1 and 2.

$$m_d(\omega_{do} - \omega_{di}) = \frac{m_p(M_i - M_f)}{T} \quad (1)$$

$$m_d\left[C_a t_{di} + \omega_{di}\left(h_{fg} + C_{pv} + t_{di}\right) - C_a t_{do} - \omega d_o\left(h_{fg} + C_{pv} t_{do}\right)\right] = 0 \quad (2)$$

Heat pump model The basic heat pump model includes component models for the evaporator, compressor, condenser, and capillary tube. Several assumptions have simplified the heat pump model. The assumptions for the heat pump unit and dryer unit are as follows.

Assumptions in the refrigerant flow path

1. The heat pump is operated at a steady state.
2. The refrigerant flow path is an ideal refrigeration cycle.
3. The pressure drop of the pipe system is negligible.
4. The tubes connecting the heat pump components are insulated.
5. The wall of the component housing is adiabatic.

Assumptions in the airflow path

1. The air duct and the drying chamber are thermally insulated.
2. The ambient conditions and specific heat capacity of air are constant.
3. The dryer is in steady-state condition and thermal equilibrium.
4. The system's air pressure is consistent, and the circulating dry air's mass flow rate is steady.
5. The drying process is under a constant rate period.
6. The air condition leaving the condenser is the same as that of the air entering the drying chamber.

Compressor model The reciprocating compressor, described by Threlkeld (1970), is given by Eq. (3). The equation 4 indicates the compressor power requirement (Teeboonma et al., 2003; Pal & Khan, 2008; Hossain et al., 2013).

$$W_h = \frac{m_r P_1 V_1}{3600}\left(\frac{n}{n-1}\right)\left\{\left(\frac{P_2}{P_1}\right)^{\frac{(n-1)}{n}} - 1\right\} \quad (3)$$

For a reciprocatory compressor

$$\eta_v = 1 + n - n\left(\frac{P_2}{P_1}\right)^{1/n}$$

$$n = \frac{C_{rp}}{C_{rv}}$$

$$W_h = m_r(H_{co} - H_{ci}) \quad (4)$$

Capillary tube model The capillary tube is used as an expansion device for pressure reduction (Pal & Khan, 2008; Hossain et al., 2013; Jolly et al., 1990). This process is isenthalpic.

$$H_{co} = H_{ei} \quad (5)$$

Fan Power Dynamic pressure losses in ducts occur due to change in direction and velocity.

$$Fan\ power\ requirement = Fan\ total\ Pressure\ \times Volumetric\ air\ flow\ rate \quad (6)$$

Evaporator model The evaporator model has been developed according to the mass and energy balance equations and incorporating air bypass factor and modified from the equations given by Teeboonma et al., 2003; Pal & Khan, 2008; Hossain et al., 2013; Jolly et al., 1990 (equation 7, 8, and 9).

$$m_{ew} = m_a(1 - BF)(\omega_{do} - \omega_{es}) \quad (7)$$

$$Q_{ea} = m_a(1 - BF)(h_{do} - h_{es}) - m_{ew}h_{ew} \quad (8)$$

$$Q_{er} = m_r(H_{eo} - H_{ei}) \quad (9)$$

Condenser model The condenser model has been developed according to the mass and energy balance equations (Teeboonma et al., 2003; Pal & Khan, 2008; Hossain et al., 2013; Jolly et al., 1990) and illustrated by equation 10 and 11.

$$Q_{ca} = m_a(C_{pa} + \omega_{di}C_{pv})(t_{co} - t_{eo}) \quad (10)$$

$$Q_{cr} = m_r(H_{ci} - H_{ei}) \quad (11)$$

Performance model Several performance models are used to evaluate the performance of the HP dryers, i.e., the specific moisture extraction rate (SMER), the coefficient of performance (COP), specific energy consumption, the moisture extraction rate (MER) (Colak & Hepbasli, 2009 (a); Colak & Hepbasli, 2009 (b); Clements, 1993; Jia, 1990; Mujumdar, 2007).

Coefficient of Performance The energy efficiency of a heat pump is defined by the COP and given by equation 12 (Chua et al., 2002; Jia, 1990; Pal & Khan, 2008; Hossain et al., 2013; Achariyaviriya et al., 2000).

$$COP = \frac{Useful\ heat\ output}{Power\ input} \quad (12)$$

Specific Moisture Extraction Ratio

Specific Moisture Extraction Rate (SMER) is the parameter used as a thermic feature of heat pump dryer performance, indicating a heat pump's efficacy. SMER is defined as the ratio between the amount of moisture evaporated and the compressor's energy and the blower (Mohanraj, 2014). SMER numbers directly measure the energy efficiency in removing water from the dried material (Minea, 2013). SMER is defined in equation 13 (Achariyaviriya et al., 2000; Colak & Hepbasli, 2009 (b), Chua et al., 2002, Prasertsan et al., 1997; Pal & Khan, 2008; Hossain et al., 2013).

$$SMER = \frac{amount\ of\ water\ evaporated\ per\ unit\ time}{energy\ input\ to\ the\ dryer} \quad (13)$$

Jia et al. (1990) and Schmidt et al. (1998) also defined SMER as $SMER_{hp}$ (14) and $SMER_{ws}$ (15).

$$SMER_{hp} = \frac{m_d}{W_h} \quad (14)$$

$$SMER_{ws} = \frac{m_d}{W_h + W_f} \quad (15)$$

Moisture Extraction Rate The MER indirectly represents dry product throughput and calculated using equation 16 (Hossain et al., 2013; Pal & Khan, 2008; Prasertsan et al., 1996).

$$MER = \frac{water\ evaporated\ from\ product}{drying\ time} \quad (16)$$

RESULTS AND DISCUSSION

SOLUTION ALGORITHM

Python programming language was used for the algorithm development. The inputs for the simulation procedure are initial and final moisture contents, product weight, total drying time, and evaporator bypass air ratio. The temperature and relative humidity for drying products are guessed values for each crop. Accordingly, the humidity of the air was calculated using a psychrometric set of equations. The humidity ratio of air entering the drying chamber is calculated by the air's known conditions entering the drying chamber. The optimum mass flow rate for the crop also a guessed value. The evaporator bypass ratio is added to the algorithm for further proceed. The compressor power requirement, specific moisture extraction rate, and coefficient of performance are significant outputs of the algorithm. The algorithm was developed for several refrigerants that can be selected, such as R12, R22, R114, R502, and R717.

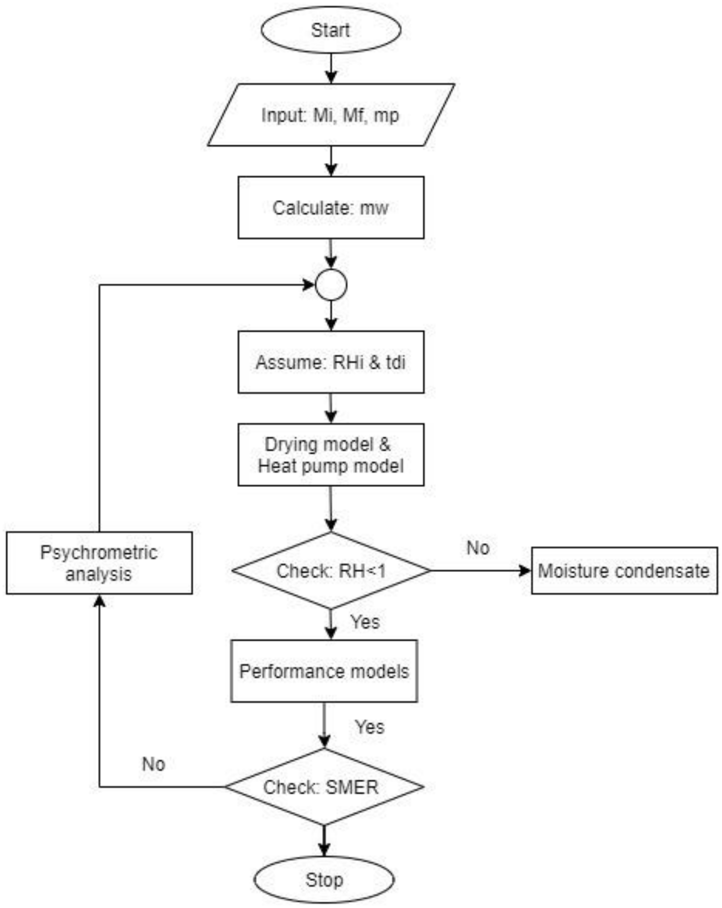

Figure 2. Flow chart for the algorithm.

VALIDATION OF THE ALGORITHM

The algorithm was validated for several crops which dried under a heat pump drying system. The selected crops were coffee (*Coffea arabica*) (Fernando et al., 2021), papaya (*Carica papaya*) (Soponronnarit et al., 2007), chestnuts (*Castanea crenata*) (Giovenzana et al., 2013), alfa-alfa (*Medicago sativa*) (Adapa et al., 2002). The data were feed to the algorithm, and calculated the design parameters. The SMER values resulted from the program were 0.719 kWh kg^{-1}, 0.363 kWh kg^{-1}, 0.490 kWh kg^{-1}, and 0.620 kWh kg^{-1}, and the corresponding SMER values were 0.709 kWh kg^{-1}, 0.374 kWh kg^{-1}, 0.520 kWh kg^{-1}, 0.644 kWh kg^{-1}, respectively. The error percentage for SMER values from literature and resulted from the program were 1.32%, 2.95%, 6.12%, and 3.82%, respectively. The results indicated that the developed algorithm provided better results for SMER and thereby demonstrated the algorithm's accuracy.

CONCLUSION Heat pump dryer algorithm was developed and tested to simulate HP dryer design components and performance. It has several refrigerants that can be selected, such as R12, R22, R114, R502, and R717. The results reported in the present work confirmed the viability of developing a computer program based on correlations, energy and mass balance, heat and mass transfer, and experimental data on the physical properties of agricultural products. There were several assumptions on developing the algorithm, which was typical routines in the HP drying process. The HP dryer code was developed, debugged, and tested. The algorithm provides output results on condenser capacity, evaporator capacity, compressor power requirement, and performance indices such as COP, SMER, and MER. The algorithm was compared and simulated and experimental results for different agricultural products. The results indicated that the developed algorithm helps design and select various components of a batch-type, closed-loop heat pump drying process under constant drying rate conditions.

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NOMENCLATURE

BF	bypass factor
C_{pa}	specific heat of dry air (kJ/kg K)
C_{pv}	specific heat of water vapor (kJ/kg K)
C_{rp}	specific heat of refrigerant at constant pressure (kJ/kg K)
C_{rv}	specific heat of refrigerant at constant volume (kJ/kg K)
H	enthalpy of refrigerant (kJ/kg)
h	enthalpy of air (kJ/kg dry air)
h_{ew}	enthalpy of condensed water at the evaporator surface temperature (kJ/kg)
h_{fg}	latent heat of vaporization of water at reference temperature of 0^{o}C (kJ/kg)
m_a	mass flow rate of dry air (kg/s)
m_d	dry mass air flow rate (kg/s)
m_{ew}	rate of moisture condensed at the evaporator surface (kg/s)
M_f	final moisture content of product (%, w.b.)
M_i	initial moisture content of product (%, w.b.)
m_p	dry mass of the product (kg)
m_r	mass flow rate of refrigerant (kg/s)
m_w	mass of moisture removed during drying (kg)
P	pressure (kPa)
Q	heat transfer rate (kW)
RH	relative humidity (%)
t	temperature of air (K)
T	total time (h)

W_h	power input to the compressor (kW)
W_f	power input to the fan (kW)
ω	humidity ratio of air (kg water/kg dry air)
η_v	volumetric efficiency

SUBSCRIPTS

a	air
c	condenser
d	drying chamber
e	evaporator
es	evaporator surface
hp	heat pump
i	inlet
o	outlet
r	refrigerant
ws	whole system