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Coordinators:

Dr. M. Mohanraj **Dr. K. Siva**
Dr. J. Manikandan **Dr. P.Jeyalakshmi**

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Department of Mechanical Engineering
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Othakkalmandapam Post, Coimbatore- 641032. India
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Numerical simulation of a heat pump assisted solar dryer for continental climate of Kazakhstan

M. Kuan[1], Ye. Shakir[1], Ye. Belyayev[2*], M. Mohanraj[3], S. Jayaraj[4], A. Kaltayev[2]

[1]Al-Farabi Kazakh National University, Dept. of Mechanics,71 Al-Farabi Ave., 050040 Almaty, Kazakhstan

[2]Satbayev University, Department of Applied Mechanics and Foundations Designed Machines, 22a Satbayev Str, 050013 Almaty, Kazakhstan, yerzhan.belyayev@gmail.com*

[3]Hindusthan College of Engineering and Technology, Department of Mechanical Engineering, Pollachi Main Road, Coimbatore – 641 032, Tamil Nadu, India

[4]Department of Mechanical Engineering, National Institute of Technology Calicut-673601, Kerala, India

Abstract

A numerical model has been proposed in this work for predicting the energy performances of the heat pump assisted solar dryer under continental climates. The numerical model is based on energy and mass balance. A new heat pump assisted solar dryer configuration is proposed to improve the performance. A comparison of results has been made between the conventional solar dryer and heat pump assisted solar dryer. The numerical simulation was performed for wide range of ambient temperatures and solar intensities. The numerical simulation results showed that heat pump assisted solar dryer is more energy efficient and produce better yield when compared to the conventional simple solar dryer. The influences of solar intensity, ambient temperature, heat pump operating temperatures are discussed.

Keywords: solar energy; solar dryer; heat pump; continental climate

1. Introduction

Drying of agricultural products is one of the energy-intensive processes in agriculture. The main energy sources for drying are liquid hydrocarbon fuel, gas and electricity. The cost of fuel for drying is now much bigger than the time it takes to grow it. Recently, more research [1]-[8] has been carried out on the use of solar energy and solar plants for drying grain, herbs, fruits, vegetables and other agricultural products. The drying technology consists in using heated solar air in special collectors and passing it through the dried material. However, the use of solar energy alone limits the adoption of such technologies in regions with low solar insolation and cold climatic regions. So to increase energy efficiency and sustainability (environmental friendly impact), such solar systems are integrated with a heat pump that is also suitable for cold climatic regions. A comprehensive review on research and development on solar assisted compression heat pump systems is given in [9]-[10].

For example, in [1] the performance of a solar dryer (SD) and a solar-assisted heat pump dryer (SAHPD) for drying of cassava chips have been investigated. The SD and SAHPD decreased the mass of cassava from 30.8 kg to 17.4 kg within 13 and 9 h at average temperatures of 40° C and 45° C, respectively. The moisture content of cassava decreased from 61% (wet basis) to 10.5%, with a mass flow rate of 0.124 kg/s. The average thermal efficiencies were 25.6% and 30.9% for SD and SAHPD respectively. In [2] thermal storage solar-assisted heat pump drying system was set up. The SAHPD can save energy consumption by 40.53% in terms of heat recovery and thermal storage. In [3] comparison of drying characteristics of apples between heat pump and solar dryer is made. Effective moisture diffusivity was found to be 2.36×10^{-8} m^2/s in the heat pump dryer, and 1.03×10^{-8} m^2/s in the solar dryer. A simulation program has been developed to evaluate the performance of a solar assisted heat-pump dryer and water heater operating under the meteorological conditions of Singapore [4]. Values of the COP and SF of the system are 6.0 and 0.62, respectively, were observed from the experimental results. An efficiency of 0.80 was obtained for the evaporator collector, whereas an efficiency of 0.77 was obtained for the air collector. A lab-scale PV-assisted solar drying system equipped with a sun tracking unit was designed and fabricated to study the drying behaviour of tomato slices during the drying process [5]. The sun tracking system profoundly shortened the drying time about 16.6% to 36.6%. In [6] mixed-mode, fluidized bed drying

system was developed using a solar energy system. The system was comprised of a solar air collector, a parabolic trough collector, and a heat pump system. The energy and exergy efficiencies of the system were found to be 50 and 26%, respectively.
In this paper a mathematical model and numerical algorithm has been created for calculating the thermal performance of the solar dryer in coupled with a heat pump under meteorological conditions of Kazakhstan.

2. System description

The heat pump assisted solar dryer consists of a solar collector, heat pump, drying chamber, and blowers. The solar collector consists of several main parts: cover of glass; absorbent plate made from aluminium; angular iron frame. The area of collector is 1 m^2. The heat pump consists of evaporator, condenser, compressor, and expansion valve. The compressor has an electrical capacity of 500 W. The drying chamber has a dimension of 1.0 m (width), 1.0 m (length), 0.3 m (height). The schematic diagram of heat pump assisted solar dryer is shown in Fig.1.

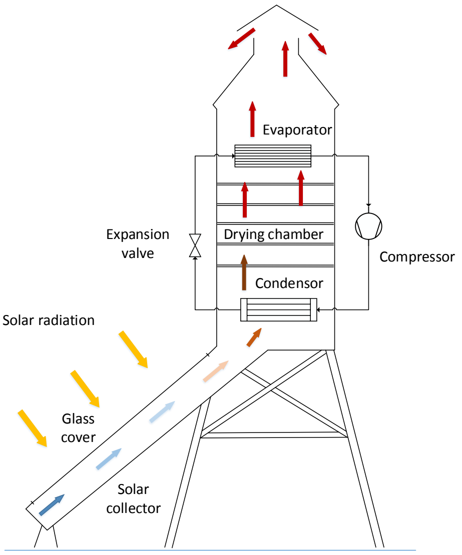

Fig. 1. Heat pump assisted solar dryer system

3. Mathematical model

To simulate the performance of heat pump assisted solar dryer the following mathematical model was formulated. Basic assumptions of mathematical model:

1) all the process are steady state;
2) pressure drop, potential, kinetic and chemical effects are assumed to be negligible in heat pump circuit;
3) compression of the refrigerant vapour is assumed to follow a polytrophic process;
4) expansion of refrigerant liquid is considered to be isenthalpic;
5) vapour losses through the side, as well as other losses are negligible;
6) the heat conduction within the dryer is negligible.

Energy balance equations for different part of system are as follow:
Energy balance for solar collector glass cover:

$$m_g \cdot C_g \cdot \frac{dT_g}{dt} = (1-\rho_g)\cdot\alpha_g\cdot G_H + (q_{r,air-g} + q_{c,air-g}) - q_{r,g-a} - q_{c,g-a} \tag{1}$$

Energy balance for air in solar collector:

$$m_{air}\cdot C_{air}\cdot\frac{dT_{cair}}{dt} = (1-\rho_g)\cdot(1-\alpha_g)\cdot\alpha_{air}\cdot G_H - (q_{r,air-g} + q_{c,air-g}) + q_{c,b-air} - m_{air}\cdot C_{air}\cdot v\cdot\frac{dT_{cair}}{dt} \tag{2}$$

Energy balance for absorber:

$$m_b\cdot C_b\cdot\frac{dT_b}{dt} = (1-\rho_g)\cdot(1-\alpha_g)\cdot(1-\alpha_{air})\cdot\alpha_b\cdot G_H - q_{c,b-air} - q_{loss} \tag{3}$$

Energy balance for the air in drying chamber:

$$m_{air}\cdot C_{air}\cdot\frac{dT_{dair}}{dt} = q_{c,c-air} + q_{c,p-air} - m_{air}\cdot C_{air}\cdot v\cdot\frac{dT_{dair}}{dx} \tag{4}$$

Fick's diffusion equations are commonly used to determine the effective diffusivity of moisture during food drying [11]:

$$\frac{dM}{dt} = \nabla^2 D_{eff} M \tag{5}$$

where, M - moisture content, t – time, D$_{eff}$ - effective diffusion coefficient [11].

$$MR = \frac{M_t}{M_o} = \frac{8}{\pi^2} e^{\frac{-\pi^2 D_{eff} t}{L^2}}$$
$$D_{eff} = 0.01751 e^{-6152.7 T_{abs}^{-1}}$$

4. Method of solution

Numerical algorithm for solution of (1)-(4) based on the fourth order Runge-Kutta method [12]-[13]. Computer program for implementation of numerical algorithm developed by means of C++ programming language. As the initial conditions for temperature at the different part of the heat pump assisted solar dryer ambient temperature were assumed. At the first time step this temperature value was used to calculate convective and radiative heat transfer coefficients. Based on this values and physical properties temperatures at the different positions of the system were calculated. In Table 1 the basic system parameters are performed.

Table 1. Basic parameters of the heat pump assisted solar dryer

Parameter	Symbol	Value	Unit
Mass of the glass cover	m_g	10.12	$kg{\cdot}m^{-2}$
Specific heat of glass	C_g	800	$J{\cdot}kg^{-1}{\cdot}C^{-1}$
Mass of air	m_{air}	0.2494	$kg{\cdot}m^{-2}$
Specific heat of air	C_{air}	1006	$J{\cdot}kg^{-1}{\cdot}C^{-1}$
Mass of plate absorber	m_b	15.6	$kg{\cdot}m^{-2}$
Specific heat of plate absorber	C_b	480	$J{\cdot}kg^{-1}{\cdot}C^{-1}$
Reflectivity of glass	ρ_g	0.0735	-
Absorptivity of glass	α_g	0.0475	-
Absorptivity of air	α_{air}	0.01	-
Absorptivity of absorber	α_b	0.95	-

5. Results and Discussion

Temperature variation of different parts of the dryer was numerically estimated for continental climate conditions of Kazakhstan. In the present paper meteorological conditions of Almaty city in Kazakhstan was considered. As the ambient temperature one day in December and July in Almaty was adopted. Fig.2 shows the temperature variation of the one day of December (2017) and July (2017).

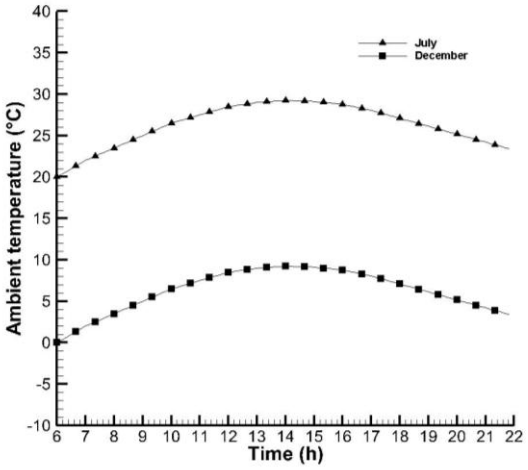

Fig.2. The temperature variation of the one day in July and December 2017

Figure 3 and 4 shows direct and diffuse solar radiation depending on environment temperature, respectively.

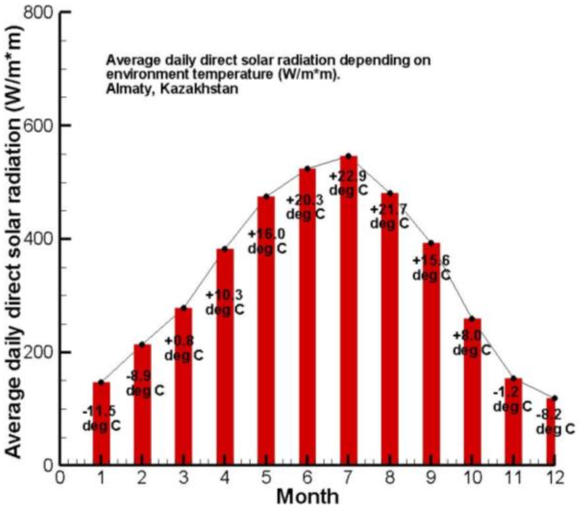

Fig. 3. The direct solar radiation in Almaty

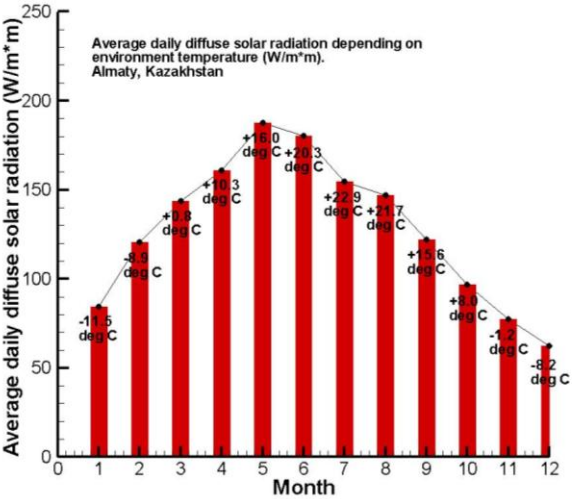

Fig. 4. The diffuse solar radiation in Almaty

The temperature variation of different parts of the dryer in function of time for the summer and winter days are presented in Fig.5 (Almaty).

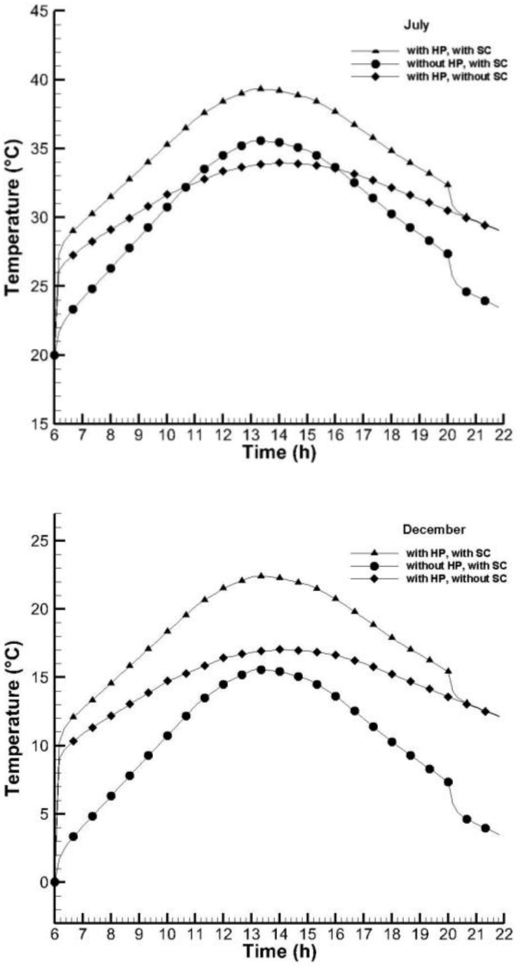

Fig.5. The temperature variation of the different solar dryer parts

According to Fig.5 three different operational modes of heat pump assisted solar dryer is considered, where HP – heat pump, SC – solar collector. As can be seen from the Fig.5, when the heat pump and the solar collector are switched on, the maximum temperature in the dryer chamber is reached 39.34º C in July and 23.1º C in December. The maximum temperature in the dryer chamber is reached 35.2º C in July and 15.3º C in December without heat pump and with solar collector. The maximum temperature in the dryer chamber is reached 33.7º C in July and 16.6º C in December with heat pump and without solar collector.

The temperature variation of solar thermal collector parts of the heat pump assisted solar dryer in function of time for the summer and winter days are presented in Fig.6 (Almaty).

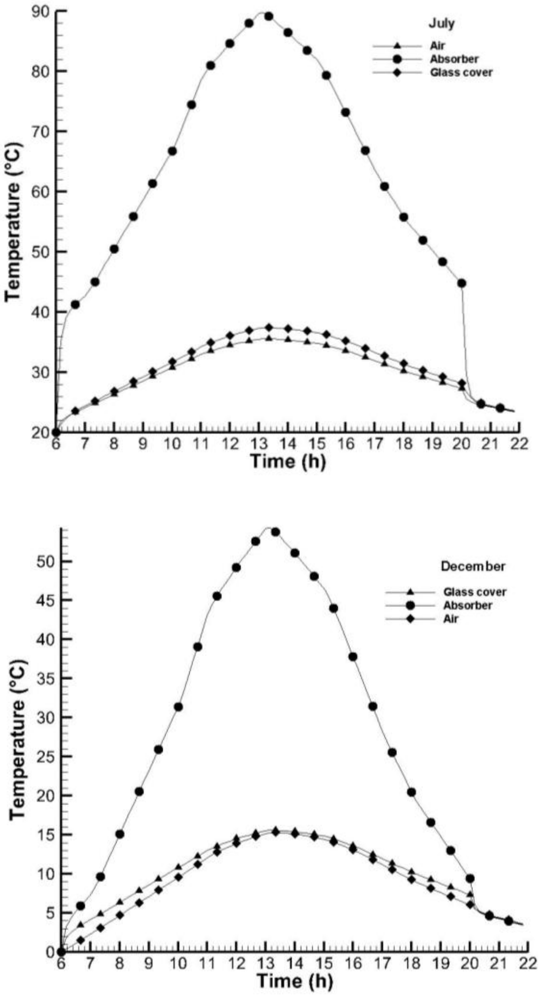

Fig.6. The temperature variation of the solar collector different parts

According to Fig.6 the heat pump assisted solar dryer solar collector operation mode: the maximum temperature absorber plate is reached 89.2º C in July and 53.8º C in December; the maximum temperature of the glass cover is reached 33.1º C in July and 15.0º C in December; the maximum air temperature in solar collector is reached 34.1º C in July and 14.8º C in December.

Fig.7 shows moisture ratio in function of time for the summer and winter days in three different heat pump assisted solar dryer operational mode. For validation of developed numerical algorithm as the drying product green banana is taken [11].

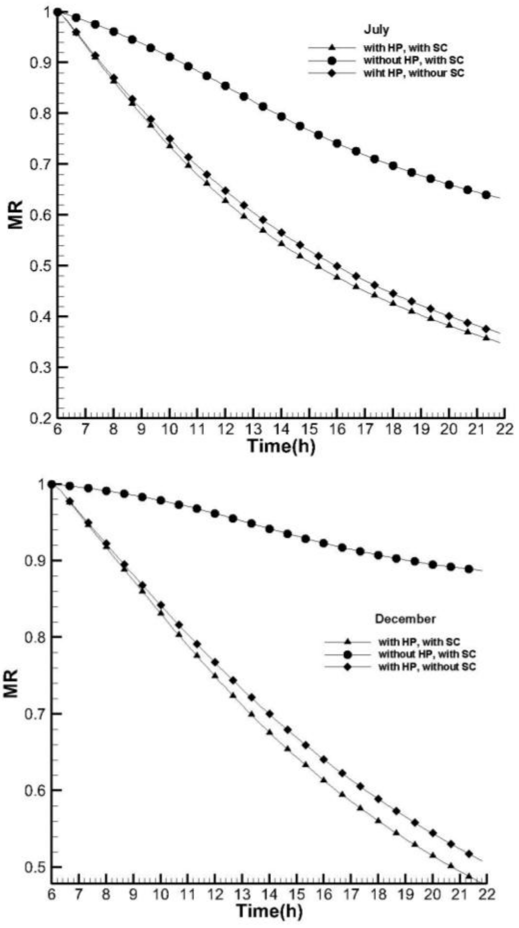

Fig.7. MR coefficient for different operational mode of dryer

According to Fig.7 the maximum drying effect is reached during using heat pump and solar collector operational mode. However difference between using heat pump case without solar collector and heat pump with solar collector is 2%. The moisture ratio is 0.63 in July and 0.89 in December, respectively without using heat pump and with using solar collector.

6. Conclusion

Numerical simulation of a heat pump assisted solar dryer under meteorological conditions of Kazakhstan has been carried out and following conclusions are drawn:

- The heat pump assisted solar dryer produced 40% improved drying effect when compared to simple solar dryer;
- Numerical simulation results for Almaty climate conditions confirm that heat pump assisted solar dryer is suitable for drying agricultural foods in remote locations of Kazakhstan.

Further, the authors are developing a commercial solar dryer for drying agricultural foods in Kazakhstan agriculture sector.

7. Acknowledgements

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