ABSTRACT

Heat pump drying of fruits, vegetables and biological materials is an interesting area of research. The main advantages of using a heat pump dryer (HPD) are the energy-saving potential with high energy efficiency and high moisture removal rate and the ability to control drying temperature and air humidity at the drying chamber inlet. The performance of the heat pump dryer can be enhanced by utilizing hybrid energy sources. The hybrid source heat pump dryer utilizes unconventional energy sources such as solar energy, ground source energy and waste heat recovery source with a heat pump system, which decreases the electric energy consumption with the improved thermal performance and drying time as compared to the simple heat pump dryer. The drying temperature range for the hybrid source heat pump dryer may be greater than the simple heat pump dryer, which improves the drying rate and energy efficiency. Various types of the simple HPD and the hybrid source HPD have been analyzed in this research, such as solar assisted HPD, HPD assisted with waste heat recovery from the engine exhaust, HPD with air conditioning and intermittent drying with solar assisted HPD. Furthermore, in view of phasing out the conventional refrigerant due to ozone layer depletion and global warming issues, the future refrigerant such as R1234yf, R1234ze (E), R152a and R600 are studied numerically for the heat pump drying applications. The R1234yf refrigerant is experimentally analyzed for the intermittent drying of food products with solar-assisted heat pump dryer.

An experimental facility of HPD has been developed to compare closed and open modes of drying on the basis of various energy, exergy and drying kinetic parameters. Total energy consumption is lowest for the closed system heat pump drying of banana and potato chips. The total energy consumptions for banana chips in the open and closed system are 3.3, 2.41 kWh and for potato chips are 3.564, 3.51 kWh, respectively. The closed system drying is found better on the basis of the performance parameters such as mass transfer coefficient, moisture extraction rate (MER), specific moisture extraction rate (SMER) and drying efficiency in the given humid and hot atmosphere for the fruits and the vegetable drying. The experimented heat pump dryer has been modeled numerically to compare various low-GWP refrigerants (R290, R600, R600a, R152a, R32, R1234yf and R1234ze(E)) as R134a substitutes. Within studied refrigerants, R152a and R32 yield better performance in terms of drying efficiency and specific moisture extraction rate; however, R152a may be more favorable for HPD due to lower GWP.

The solar and infrared assisted HPD has been developed and various thermal, economic and exergoeconomic performance parameters such as coefficient of performance (COP), overall heating coefficient of performance (OHCOP), energy requirement, drying time, energy efficiency, drying efficiency, MER, SMER, exergy destruction, investment cost, running cost, payback period, exergy destruction cost, exergoeconomic factor and the cost ratio have been evaluated for drying of different materials. The hybrid source heat pump dryer is found better in terms of SMER and energy efficiency as compared to the simple HPD. Solar-assisted HPD (SAHPD), infrared-assisted HPD and solar-infrared assisted HPD (SIAHPD) are compared and estimated that SAHPD system is better based on the basis of SMER, and SIAHPD is better than others based on MER in the given humid and hot atmosphere for drying of banana chips. The drying cost of the material per kg and the total energy consumption to the system are minimum for the SAHPD and it is highest for the infrared assisted heat pump dryer. The drying cost per kg of material for the banana chips in simple HPD, IAHPD, SAHPD and SIAHPD are 0.488 $/kg, 0.497 $/kg, 0.469 $/kg and 0.484 $/kg, respectively.

Heat pump dryer assisted with the heat recovery from the diesel engine exhaust is developed and the experimental analyses is done by using energy-exergy and ecomonomic-exergoecomic methodology. Performance is compared with simple HPD for both open and closed loops. The radish chips are dried to remove moisture from 93.5% to 10.5% at an air velocity of 1.0 m/s in the drying chamber. Both energy and exergy efficiencies are found highest for waste heat recovery-assisted system. SMER (2.4 kg/kWh) and OHCOP (6.72) are higher for the waste heat recovery assisted system. The payback period for the HPD assisted with waste heat recovery over the simple HPD is 33 months. The lowest exergoeconomic factor is for expansion device in simple HPD and HPD assisted with waste heat recovery in a closed-loop system with determined values as 0.0918 and 0.1348. The total exergy destruction cost for the simple and hybrid systems is 0.10148 $/h and 0.1266 $/h, respectively.

The experiment is also performed for different intermittency ratios for radish drying with a solar-assisted heat pump dryer using future refrigerant R1234yf. The effects of total drying time (on-period + off-period) on various energetic, exergetic, and economic performances are investigated to extract moisture from 92.4% to 11.9%. Energy efficiency and drying efficiency are estimated higher for a lower intermittency ratio. The moisture extraction rate and specific moisture extraction rate are higher for intermittent drying as compared to continuous drying and increase with a decrease in intermittency ratio. The economic analysis concludes that the payback period is lower for a lower intermittency ratio. The payback period for intermittency ratio of 1, 0.66, 0.33

and 0.2 are estimated as 1.617 years, 1.459 years, 1.384 years, and 1.347 years, respectively. Present experimental thermo-economic analysis reveals that intermittent drying is much better (maximum enhancement of specific moisture extraction rate is 60.6%, that of energy efficiency is 56.4% and maximum reduction of drying cost is 37.9% with studied conditions) than continuous drying.

An integrated heat pump system for combined heat pump drying and air conditioning is experimentally studied as well. The main advantage of this combined system is that it gives the performance of both heat pump drying and air conditioning with a single energy input source. The experiment is performed for different atmospheric conditions to estimate the performance of the combined system using future refrigerant R1234yf in the heat pump system. The effects of the drying time, air inlet velocity and air inlet temperature to the evaporator and the condenser on the performance of the air conditioning and drying are investigated. The coefficient of performance for the combined operation is found to be much higher than that for the individual operation (heat pump drying or air conditioning), with an average value of 7.456 in the input temperature range of 26-45°C. The cooling air temperature and the humidity are 22.6-24.7°C and 40.4-50.2% (are in the comfort zone) with drying temperature of 62.1-63.9°C for the atmospheric temperature of 42-45°C. Hence, this system can be used for both drying and air conditioning purposes for the maximum atmospheric temperature of 45°C.