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Table of Contents

Contents	Page No.
Certificate	ii-iv
Acknowledgement	v-vi
Table of Contents	vii-x
List of figures	xi-xiv
List of tables	xv-xvi
List of symbols	xvii-xxii
Abstract	xxiii-xxvi
1. Introduction	1-16
1.1 Motivation	1
1.2 Heat pump dryer	6
1.2.1. Air source heat pump dryer	7
1.2.2. Ground source heat pump dryer	8
1.2.3. Chemical source heat pump dryer	9
1.3 Hybrid source heat pump dryer	10
1.3.1. Solar assisted heat pump dryer	10
1.3.2. Microwave assisted heat pump dryer	12
1.3.3. Infrared assisted heat pump dryer	12
1.3.4. Radio frequency assisted heat pump dryer	13
1.4 Contribution of the study	14
1.5 Thesis structure	15

2. Literature review	17-54
2.1 Theoretical studies on simple heat pump dryer	17
2.2 Experimental studies on simple heat pump dryer	26
2.3 Theoretical studies on hybrid heat pump dryer	42
2.4 Experimental studies on hybrid heat pump dryer	44
2.5 Research gaps	53
2.6 Objectives of present study	53
3. Experimentation on simple heat pump dryer	55-79
3.1 Experimental setup and procedure	55
3.2 Data analysis	60
3.2.1. Experimental uncertainty	64
3.3 Results and discussion	
3.4 Highlights	78
4. Theoretical analysis of heat pump dryer	81-105
4.1 Modeling and simulation	82
4.1.1. Compressor model	84
4.1.2. Condenser model	85
4.1.3. Evaporator model	87
4.1.4. Capillary tube model	88
4.1.5. Fan model	89
4.1.6. Dryer model	89
4.1.7. Simulation and validation	91
4.2 Results and discussion	94
4.3 Highlights	104

5. Experimentation on solar-infrared assisted heat pump dryer	107-130
5.1 Experimental setup and procedure	107
5.2 Data analysis	111
5.3 Results and discussion	114
5.4 Highlights	129
6. Experimentation on waste heat recovery assisted heat pump dryer	131-152
6.1 Experimental setup and procedure	131
6.2 Data analysis	135
6.3 Results and discussion	139
6.4 Highlights	151
7. Experimentation on intermittent drying with solar assisted heat pump dryer	153-173
7.1. Material and methods	154
7.2 Data extraction	157
7.3 Results and discussion	160
7.4 Highlights	172
8. Experimentation on heat pump dryer integrated with air conditioning	175-193
8.1. Material and methods	176
8.2 Data extraction	179
8.3. Experimental results and discussion	181
8.4 Highlights	192
9. Concluding remarks and future scope	195-197

9.1 Conclusions	195
9.2 Future scope	197
References	199-212
List of publications	

.....

List of Figures

Fig. No.	Title	Page No.
Fig. 1.1	Classification of heat pump dryer	7
Fig. 1.2	Schematic diagram of heat pump dryer	8
Fig. 1.3	Schematic diagram of ground source assisted heat pump dryer	9
Fig. 1.4	Schematic diagram of chemical source heat pump dryer	10
Fig. 1.5	Schematic diagram of Solar assisted heat pump dryer	11
Fig. 1.6	Schematic diagram of microwave assisted heat pump dryer	12
Fig. 1.7	Schematic diagram of infrared assisted heat pump dryer	13
Fig. 1.8	Schematic diagram of radio frequency assisted heat pump dryer	14
Fig. 3.1	Schematic diagram of the heat pump drying system	56
Fig. 3.2	Photograph of the developed experimental setup	57
Fig. 3.3	Variation in energy requirement with drying time	68
Fig. 3.4	Variation in drying temperature with drying time	69
Fig. 3.5	Variation of relative humidity at dryer inlet with drying time	70
Fig. 3.6	Change in moisture ratio with drying time	70
Fig. 3.7	Variation in water loss from the product with drying time	71
Fig. 3.8	Variation in volumetric heating capacity with time	71
Fig. 3.9	Variation in COP with drying time	72
Fig. 3.10	Variation in moisture extraction rate with drying time	73
Fig. 3.11	Specific moisture extraction rate with drying time	74
Fig. 3.12	Variation of drying efficiency with drying time	75

Fig. 3.13	Variation in energy efficiency with drying time	76
Fig. 3.14	Variation in the total exergy destruction with drying time	78
Fig. 4.1	Schematic diagram of open type HPD	82
Fig. 4.2	Heat pump cycle on T-s diagram	83
Fig. 4.3	Various processes on psychrometric chart	84
Fig. 4.4	Various heat transfer zone in evaporator	87
Fig. 4.5	Flow chart of the overall simulation	93
Fig. 4.6	Variation of dryer outlet temperature with drying time	97
Fig. 4.7	Variation of dryer outlet relative humidity with drying time	97
Fig. 4.8	Variation of moisture ratio with drying time	98
Fig. 4.9	Comparison of change in MER with drying time	99
Fig. 4.10	Variation of SMER with drying time	99
Fig. 4.11	Variation of moisture extraction rate with material moisture content	100
Fig. 4.12	Variation of drying efficiency of HPD with drying time	100
Fig. 4.13	COP of different refrigerants at different atmospheric condition	101
Fig. 4.14	SMER of different refrigerants at different atmospheric condition	102
Fig. 4.15	Comparison of total exergy destruction with different refrigerants	104
Fig. 5.1	Graphical representation of the heat pump drying system	108
Fig. 5.2	Photograph of developed experimental setup of SIAHPD and drying chamber interior	109
Fig. 5.3	Photograph of the banana chips before drying (a) and after drying (b)	115
Fig. 5.4	Variation in energy requirement with drying time	117
Fig. 5.5	Variation in COP with drying time	119

Fig. 5.6	Variation in energy efficiency with drying time	120
Fig. 5.7	Change in moisture content with drying time	120
Fig. 5.8	Variation in moisture extraction rate with drying time	121
Fig. 5.9	Variation of specific moisture extraction rate with drying time	122
Fig. 5.10	Variation of drying efficiency with drying time	123
Fig. 5.11	Variation in MER with the moisture content of product	124
Fig. 5.12	Variation in the total exergy destruction with drying time	126
Fig. 6.1	Graphical representation of diesel engine exhaust heat recovery assisted HPD	132
Fig. 6.2	Laboratory prototype of WHR assisted HPD	132
Fig. 6.3	Variation of exhaust gas and water temperature in WHR system	141
Fig. 6.4	Moisture content with drying time	141
Fig. 6.5	OHCOP variation according to drying time	143
Fig. 6.6	Variation in energy efficiency with drying time	143
Fig. 6.7	Variation in MER with drying time	144
Fig. 6.8	Variation of SMER with drying time	145
Fig. 6.9	Variation in exergy destruction with drying time	145
Fig. 7.1	Schematic of the presentation of solar-assisted-HP dryer for intermittent drying	155
Fig. 7.2	Experimental facility of SAHPD for intermittent drying	155
Fig. 7.3	Solar radiation and water temperature variation with day hour	161
Fig. 7.4	Moisture content variation of product with total drying time	163
Fig. 7.5	OHCOP variation with total drying time	164
Fig. 7.6	MER variation with total drying time	165
Fig. 7.7	SMER variation with total drying time	166

Fig. 7.8	Drying efficiency variation with total drying time	167
Fig. 7.9	Energy efficiency fluctuations with total drying time	168
Fig. 8.1	Schematic of the presentation of HP dryer with cooling of air	177
Fig. 8.2	Developed experimental facility of HP dryer with cooling of air	178
Fig. 8.3:	Human thermal comfort zone and various air process on psychrometric chart	182
Fig. 8.4	Variation of evaporator outlet temperature according to atmospheric temperature	183
Fig. 8.5	Condenser outlet temperature variation with atmospheric temperature	184
Fig. 8.6	Evaporator outlet relative humidity with atmospheric temperature	184
Fig. 8.7	OCCOP variation with evaporator inlet temperature	185
Fig. 8.8	OSCOP variation with evaporator inlet temperature	186
Fig. 8.9	Temperature and relative humidity variation with atmospheric temperature	187
Fig. 8.10	Temperature and relative humidity variation with condenser inlet temperature	188
Fig. 8.11	SMER for drying at mean atmospheric temperature of 38.4°C	188
Fig. 8.12	Exergy destruction of the system at different atmospheric temperature	189
Fig. 8.13	Component wise exergy destruction at atmospheric temperature of 38.4°C	190
Fig. 8.14	Overall system energy efficiency at mean atmospheric temperature of 38.4°C	190

List of Tables

Table No.	Title	Page No.
Table 2.1	Literature review on numerical analysis of simple heat pump dryer	22
Table 2.2	Literature review on experimental analysis of simple heat pump dryer	34
Table 2.3	Literature review on theoretical analyses of hybrid source heat pump dryer	43
Table 2.4	Literature review on experimental analysis of hybrid source heat pump dryer	48
Table 3.1	Specification of the different components of the HPD system	57
Table 3.2	Technical specification and uncertainty of measuring instrument	58
Table 3.3	Performance comparison of experimental results	65
Table 3.4	Exergetic performances of components for banana and potato chips drying	77
Table 4.1	Properties of considered refrigerants	81
Table 4.2	Validation of the simulation result with experimental data	94
Table 4.3	Performance comparison HPD for different refrigerants	95
Table 4.4	Irreversibility (W) and exergy efficiency of HPD components	103
Table 5.1	Comparison of various parameters	116
Table 5.2	Irreversibility (kW) and exergy efficiency of different components	125
Table 5.3	Economic parameters of components of drying system	127
Table 6.1	Exergy destruction and efficiency of different components	139

Table: 6.2	Comparison of various performance parameters of HPD with WHR	146
Table 6.3	Economic parameters of different components of HPD with WHR	148
Table 6.4	Exergoeconomic parameters of HPD with WHR	150
Table 7.1	Performance comparison of experimental result for intermittent drying	162
Table 7.2	Component wise exergy destruction (kW) and efficiency for intermittent drying	169
Table 7.3	Economic analysis for intermittent solar-assisted-HP dryer	170
Table 8.1	Component-wise irreversibility and exergy efficiency of HPD with air conditioning	189
Table 8.2	Economic analysis for heat pump drying with air conditioning	191

List of Symbols

Nomenclatures

$2A$	Wavy height (m)
A_{fr}	Condenser frontal area (m^2)
A_i	Tube inside area (m^2)
A_o	Total outer surface area including fin and tube (m^2)
B_i	Biot number
c	Exergy cost per unit (\$/kWh)
c_{pam}	Specific heat of moist air (kJ/kg-K)
c_{pa}	Specific heat of dry air (kJ/kg-K)
c_{pv}	Specific heat of water vapor air (kJ/kg-K)
C_L	Cost of labor (\$)
C_L	Labor cost (\$)
C_m	Maintenance cost (\$)
C_{IC}	Initial investment cost (\$)
C_p	Energy requirement cost (\$)
\dot{C}_{RU}	Operating cost of drying system (\$)
C_{RM}	Fresh product cost (\$)
\dot{C}_{Total}	Total cost of drying system (\$)
C_F	Total profit (\$)
\dot{C}_x	Exergy cost rate (\$/h)
D_{ha}	Hydraulic diameter of air side (m)
DR	Drying rate (1/s)
D_{eff}	Effective diffusivity (m^2/s)

e_x	Specific exergy (kJ/kg)
E_{xin}	Exergy input (kW)
E_{xout}	Exergy output (kW)
E_{dest}	Exergy destruction (kW)
f	Friction factor of air
f_{ex}	Exergoeconomic factor
F_p	Fin pitch (m)
F_h	Fin height (m)
G_a	Mass velocity of air (kg/m ² -s)
h	Specific enthalpy (kJ/kg)
h_{fg}	Latent heat of vaporization (kJ/kg)
h_a	Air heat transfer coefficient (W/m ² -K)
h_m	Air mass transfer coefficient (kg /m ² -s)
i	Interest rate
k	Thermal conductivity (W/m-K)
k_c	Drying constant (1/s)
L	Half thickness of chips
L_f	Length between two wavy fin (m)
L_d	Length of fin (m)
LMTD	Log mean temperature difference (K)
\dot{m}_a	Air mass flow rate (kg/s)
m_p	Weight of drying product (kg)
m_{pt}	Mass of drying material at any time (kg)
\dot{m}_r	Refrigerant mass flow rate (kg/s)
M_i	Initial wet weight of the product (kg)

M_d	Final dry weight of product (kg)
M_o	Initial moisture content of material (wet basis)
M_t	Moisture content of product at any time (wet basis)
M_{eq}	Equilibrium moisture content (wet basis)
MC	Moisture content (wet basis)
MR	Moisture ratio
m_w	Mass of water in product (kg)
\dot{m}_{hw}	Mass flow rate of hot water (kg/s)
n	Time period of payment
N	Speed of compressor (rpm)
Nu	Nusselt number
P_p	Payback period
P	Pressure (bar)
Pr	Prandtl number
p_t	Transverse pitch of fin (m)
Q	Heat transfer rate (kW)
R_{ex}	Ratio of exergy destruction to purchased equipment cost
R_c	Return of capital
Re	Reynolds number
S_f	Fin spacing (m)
t_d	Drying time (hour)
t_{op}	Annual operation time (hour)
s	Specific entropy (kJ/kg-K)
T_o	Dead state temperature (K)
T	Temperature (°C)

T_d	Dew point temperature ($^{\circ}\text{C}$)
T_f	Fin thickness (m)
UA	Product of overall heat transfer coefficient and area (W/K)
V_a	Air velocity (m/s)
V_s	Swept volume of compressor (m^3)
W	Power input (kW)

Greek symbols

α	Intermittency ratio
η_{ex}	Exergy efficiency
η_{en}	Energy efficiency
η_{isen}	Isentropic efficiency of compressor
η_f	Fin efficiency
η_o	Overall efficiency of fin
η_{fn}	Fan efficiency
η_v	Volumetric efficiency of compressor
ω	Specific humidity of drying air (kg water/kg dry air)
ε	Emissivity factor
σ	Stephan–Boltzman constant ($\text{W}/\text{m}^2\text{-K}^4$)
φ	Maintenance factor
μ	Dynamic viscosity ($\text{N}/\text{s}\text{-m}^2$)
ρ	Density (kg/m^3)
v	Specific volume (m^3/kg)

Abbreviations

COP_{hp}	Coefficient of performance of heat pump system
COP_{ws}	Coefficient of performance of the whole dryer system

CR	Cost ratio
CRF	System recovery factor
DC	Drying chamber
HP	Heat pump
HPD	Heat pump dryer
HE	Heat exchanger
IAHPD	Infrared assisted heat pump dryer
MER	Moisture extraction rate
MC	Moisture content
OHCOP	Overall-heating coefficient of performance
OCCOP	Overall cooling coefficient of performance
OSCOP	Overall system coefficient of performance
PEC	Cost of purchased equipment (\$)
RH	Relative humidity
SAHPD	Solar-assisted heat pump dryer
SIAHPD	Solar-assisted-infrared-assisted heat pump dryer
SMER	Specific moisture extraction rate
SEC	Specific energy consumption
SWH	Solar water heater
WHR	Waste heat recovery
SWHE	Solar water heat exchanger

Subscripts

a	air
abs	absorbed
comp	compressor

cond	condenser
evap	evaporator
exp	expansion device
in	input
IR	infrared
M	drying material
out	output
r	refrigerant
w	water
hw	hot water
wb	wet basis
wi	hot water inlet
wo	hot water outlet

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 economic-exergoeconomic 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.