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ORIGINAL RESEARCH ARTICLE

INFLUENCE OF ENERGY RECOVERY SYSTEM ON THE ENERGY EFFICIENCY OF A FLAT-BED DRYER IN THE DRYING OF TURMERIC

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ABSTRACT

Drying is one of the most energy intensive unit operations in agricultural and food processing industry. Energy costs represent a major fraction of cost of operation of a mechanical dryer, therefore, the more efficient a dryer uses its energy supply, the lesser its cost of operation and the better it impacts on profitability of drying process. A flat-bed dryer of 25kg capacity was developed and fitted with air-to-air indirect mixing heat exchanger (Heat Recovery Unit, HRU) at the vent of the drying chamber. The dryer was tested to determine the impact of exhaust vent waste heat recovery on its energy efficiency and cost of operation. Turmeric, an important spice crop was dried at three temperatures of 60°C, 65°C, and 70°C under two operating conditions; (i) without HRU (C-I) and (ii) with HRU (C-II). The result show thermal efficiency, at C-I it was found to be 28%, 27% and 27% at 60°C, 65°C and 70°C respectively and for C-II it was 42%, 42%, and 40% at 60°C, 65°C, and 70°C respectively. This indicates that the overall thermal efficiency was improved by 15% for C-II at 65°C as compared to C-I at 65°C. ANOVA show there is significant different (P< 0.05) between C-II and C-I as regards thermal efficiency. The result also showed that specific energy consumption was reduced for all drying temperatures levels of C-II as compared to C-I and the result shows that testing condition C-II, at 65°C has the lowest specific energy consumption of 1.79(kWh/kg) while C-I at 60°C has the highest value; 2.37 (kWh/kg), this showed significant different (P< 0.05).Drying curves of turmeric were plotted and it was found that C-II performed better in drying turmeric since the moisture lose was faster than in C-I and the drying time was lowered by 4hrs for C-II at 65°C compared to C-I 65°C. The average Return on Investment (ROI) of HRU was calculated considering average of 260 working days or 130 batch drying operation per annum with one drying cycle per two working days and was found to be 0.61 and the payback period was 19 months. It was concluded that the developed flatbed dryer can be used to dry 25 kg of turmeric per batch in 25 hours drying time using operating condition C-II, 65°C which showed better quality in terms of energy efficiency and drying rate.

1.0 Introduction

Drying is an important preservation process which reduces water activity through the decrease of water content to a level safe for avoiding potential deterioration and contamination during long storage periods (Hosain *et al.*, 2014). The process of moisture removal requires a large amount of energy considering that one of the characteristics of agricultural production is production in large quantity and for each kilogram of water vaporized 2,257 kJ of energy is required. Cost of thermal energy is a major fraction of cost which is incurred in mechanical drying (Thakur and Gupta, 2006). Therefore, the higher the thermal energy efficiency of a dryer the lesser will be its cost of operation. Use of energy resources has an obvious impact on the environment. These reasons explain the need to investigate potential energy saving options that can have impact on both economic and environmental issues (Timothy *et al*.,2011).

Dryers are one of the most important equipment in food processing industries. Many dryers have been developed and used to dry agricultural products in order to improve their storage conditions. Most of these dryers use either expensive source of energy such as electricity, hydrocarbons (coal, propane gas, and liquefied natural gas) (Berinyuy, 2000) or a combination of solar energy and other forms of energy. Energy consumption is of interest to dryer manufacturers, as it is a key index of its market value (Kudra, 2004). Low energy consumption is critical for dryer users who deal with commodity materials and inexpensive products as it affects running costs. Factors affecting the energy requirements in drying includes, the produce moisture content (MC), the type and variety of produce, the drying air relative humidity (RH) and airflow rate; all affects the drying rate, and thus the energy requirements of the drying process, (Aviara *et al*., 2004). Therefore, it is relevant to specify these factors when quantifying the energy use and efficiency of a drying system

The largest portion of waste thermal energy in most of the convectional drying processes appears to be in the exhaust stream (Timothy *et al*., 2011). Recovering and reusing energy to preheat inlet air is one way to increase energy efficiency of a dryer. One of the means of heat recovery from the exhaust air stream involves the use of heat exchangers. Conventional dryers usually operate at 30-70% efficiency levels (Jangam *et al.,* 2010). Hence, drying is an area that is desperate for energy efficient technology.

1.1 Turmeric

Turmeric was considered for this drying study because of its share production volume and its economic importance to Tamilnadu State of India as an export spice. Turmeric is usually dried as a whole or in coarsely cut form to a hygienically safe moisture level (around 10%). In the tropical and subtropical regions, the plant material is commonly spread on the ground, and sometimes on raised platforms or racks and sundried for several days and this comes with inherent problem of contamination by dust particles, animal droppings, toxins from moulds, discolouration, and long drying time (Subbulakshmi and Naik, 2002).

Several mechanical dryers have been developed to accelerate the drying process, to improve the hygienic conditions and to maintain constant drying temperatures within 45°C and 60°C in order to minimize the loss of volatile oils and prevent discoloration (Ute *et al*., 2007). Though mechanical dryers, powered by electricity or fossil fuel, help in producing quality products in large scale, they are seldom adopted by small- scale entrepreneurs and farmers of most developing countries, due to heavy installation costs involved and large operating cost because of its being energy intensive process (Senadeera *et al.,* 2007).

The objectives of this study were to determine and compare energy efficiency and performance characteristics of a dryer with and without sensible heat recovery from the exhaust stream of the drying chamber and to analyse the economics of the drying system.

2. Materials and Methods

A flatbed dryer with a raw product capacity of 25kg was outfitted with a heat recovery unit (HRU) heat exchanger for this study.

2.1 Drying Chamber

A double wall metal bin of size 1.15m ×1.15m× 0.52m was made using 18gauge M.S. sheet and angle irons of 25 × 25 × 3 mm size. The bin was covered with a hood 0.3m high and having a rectangular opening (0.36m × 0.06m) at the top which the heat recovery unit fits into. The bin was built such that it could be dismantled easily for transportation. The drying chamber was insulated using polystyrene sheet with a thickness of 0.025m. A platform for tray arrangement was made 0.32m from the bottom and two doors each with dimension of 0.5m × 0.2m were in-fitted.

2.2 Design of Heat Recovery Unit (HRU)

The heat Recovery Unit (Figure 1) is an air-to-air indirect mixing corrugated plate heat exchanger type which is connected to the exhaust of the dryer on outlet flow channel and blower inlet in the inlet flow channel by a 152mm PVC pipe. It is a double wall metal box 0.52m × 0.51m × 0.18m (Figure 2), made of 18gauge M.S sheet and 25mm polystyrene sheet used in-between the walls have insulation. A grove of 0.3m × 0.015m was made on both breadth sides of the wall into which corrugated aluminium sheet creates flow channel inside the metal box as inlet and outlet.

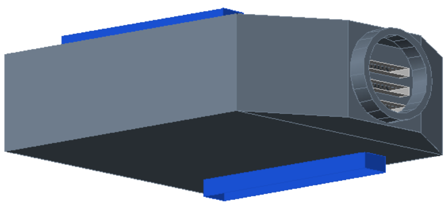

Figure 1: Conceptual view of Heat Recovery Unit

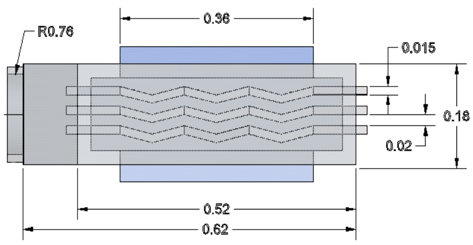

Figure 2: side x-ray view (dimensions are in m)

Each flow channel has a two aluminium sheet 0.005m with a gap of 0.015m between them. The angle of corrugation is 37 degree. One of the breadth sides was covered to create an outlet in which a 6inch PVC elbow can fix into. The heat exchanger was connected to the blower so that the blower sucks air into the heater via the heat exchanger.

Assumption were that no heat is lost to the environment that is, heat lost equals heat gain and the flow rate of both hot and cold stream is same; the following equations were used to calculate the quantity of heat transfer, and the heat transfer area required.

Properties of air (at atmospheric pressure)
Inlet temperature of cold stream, T_{c1} (°C)
Outlet temperature of cold stream, T_{c2} (°C)
Inlet temperature of hot stream, T_{h1} (°C)
Outlet temperature of hot stream, T_{h2}(°C)
Kinematic viscosity of air at exhaust vent, v_h(m^2/s)
Kinematic viscosity of air at ambient, v_c(m^2/s)
Thermal conductivity of air at exhaust, K_h (W/(m°C)
Thermal conductivity of air at ambient, K_c(W/(m°C)
Density of air at exhaust vent, ρ_h(kg/m^3)
Density of air at ambient, ρ_c(kg/m^3)
Velocity of hot stream, u_h (m/s)
Velocity of cold stream, u_c (m/s)
Specific heat capacity of air, Cp_a (kg°C)

Thermal conductivity of Al, K_a (W/m°C)

According to Osborne Reynolds, for forced convection, there exist two types of flows:

Laminar flow (Reynold number, N_{Re}< 2000)
Turbulent flow (Reynold number, N_{Re}> 4000)

N_{Re} between 2000 and 4000 indicates transition from laminar to turbulent flow that is transient flow. The formula used to calculate the convective heat transfer coefficient is dependent on the type of flow, turbulent or laminar (Rajput, 2012).

Reynolds number, $NRe = \rho ud/\mu$ (1)

And kinematic viscosity, $v = \mu/\rho$ (2)

Therefore, $NRe = ud/v$ (3)

where, d= Characteristic length (m)
ρ= Density of air (kg/m³)
u= Velocity of stream (m/s)
μ= Viscosity (mPa.s)

According to Rajput, (2012), the characteristic length, d(mm) for a rectangular duct can be calculated by equation (4)

$$d = 2lb/(l + b) \quad (4)$$

l = Height of the duct (mm)
b = Breadth of the duct (mm)

In other to determine the value of convective heat transfer coefficient, *h,* Nusselt number was used. Nusselt number, N_{Nu} is the ratio of heat flow rate by convection process under a unit temperature gradient to the heat flow rate by conduction process under a unit temperature gradient through a stationary thickness of *d*in meters.

$$N_{Nu} = hd/k \quad (5)$$

Nusselt number is also a function of Reynolds number and Prandtl number (N_{Pr}).
For transient flow, Nusselt number is given by (Singh and Heldman, 2013).

$$N_{Nu} = \frac{(f/8)(N_{Re} - 1000)N_{Pr}}{1+12.7(f/8)^{0.5}(N_{Pr}^{2/3} - 1)} \quad (6)$$

where:

$$f = \frac{1}{(0.790 \ln N_{Re} - 1.64)^2} \quad (7)$$

N_{Re} = Reynolds number
N_{Pr} = Prandtl number

For turbulent flow over a plate the Nusselt number from Colburn analogy is given by (Rajput, 2012).

$$N_{Nu} = 0.029(N_{Re})^{0.8}(N_{Pr})^{0.33} \quad (8)$$

Prandtl number, N_{Pr} is the ratio of kinematic viscosity (v) to thermal diffusivity (α)

$N_{Pr} = \rho v C_P/k$ (9)

1) Calculating overall heat transfer coefficient, U

$$\frac{1}{U} = \frac{1}{h_c} + \frac{\Delta x}{K_a} + \frac{1}{h_h} \quad (10)$$

where U = Over all heat transfer coefficient ($Wm^{-2o}C$)

h_c =Convective heat transfer coefficient of cold stream ($Wm^{-2o}C$)

k_a =Thermal conductivity of aluminium (W/m°C)

h_h = Convective heat transfer coefficient of hot stream ($Wm^{-2o}C$)

2) Calculation heat transfer area, quantity of heat transfer, Q is given as

$$Q = UA\Delta T_{lm}(CF) \quad (11)$$

$\Delta T_{lm}(CF)$ = Log mean temperature difference for counter-flow heat exchanger

$$\Delta T_{lm}(CF) = \frac{\Delta T_A - \Delta T_B}{\ln\frac{\Delta T_A}{\Delta T_B}} \quad (12)$$

ΔT_A = difference between the hot inlet and cold outlet stream temperature

ΔT_B = difference between the hot outlet and cold inlet stream temperature

ΔT_{lm} for cross flow is calculated by incorporating correction factor (F) to the expression of log mean temperature difference of counter flow heat exchanger.

$$\Delta T_{lm} = F.\Delta T_{lm}(CF) \quad (13)$$

The correction factor was obtained from the calculation of two ratios P and R associated with the inlet and outlet temperatures of the two fluids using the standard graph (Holman, 2002).

If no heat is lost in the heat exchanger, then quantity of heat transfer

$$Q = Mw_h.Cp_a.(T_{h1} - T_{h2}) \quad (14)$$

Therefore, using equation (11), heat transfer area, A was calculated.

3) Calculating the required insulation thickness

The casing of the exchanger was fabricated using composite wall with three layers made up of, mild steel - glass wool - mild steel. Using mild steel of 0.0012m thickness (x_m), and T_l and T_4 were taken as T_{hl} and T_{cl} respectively. Insulation thickness, (x_i) was calculated by Fourier's law.

$$Q = \frac{T_1 - T_4}{\frac{x_m}{K_m} + \frac{x_i}{K_g} + \frac{x_m}{K_m}} \quad (15)$$

where:

Q = Quantity of heat transferred (W/m^2)

x_m= Thickness of mild steel (m)

x_i = Thickness of insulation material (m)

T_l= Inlet temperature of hot stream (°C)

T_4 =Inlet temperature of cold stream(°C)

k_m= Thermal conductivity of mild steel(W/m°C)

k_g =Thermal conductivity of insulation(W/m°C)

2.3 Dryer layout

The dryer is an electric powered flatbed dryer with configuration including the dryer chamber, heating chamber, electric blower, heat recovery unit (HRU) and control panel (Figure 3). A centrifugal type air blower powered by a three phase 1hp electric motor was used. A supply shunt was made at the blower's suck-in opening to vary the inlet air flow rate. The blower has the capacity to move air flow rate up to 2.5m^3/min. Electric heaters was required to heat the air moved by the blower before the heated is moved to the plenum chamber. Four coils, 1.5kW each were mounted concentrically inside a M.S. sheet (18gauge) cylinder of 0.285m diameter and 1.1m length to for the heating chamber. The cylinder was insulated by using asbestos rope and Plaster of Paris to reduce the heat loss due to radiation. The control panel consist of switches for both the blower and the heaters and a thermostat to regulate temperature. The dryer was fitted with HRU as shown in Figure 4

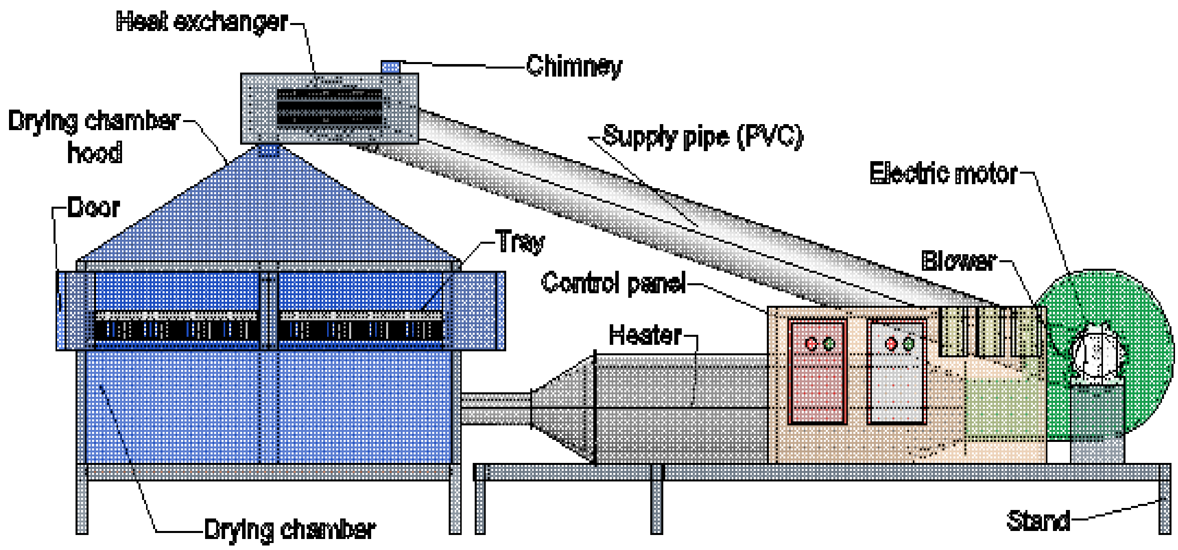

Figure 3: Conceptual front view of Flat-bed dryer with HRU

Figure 4:Flat-bed Dryer fitted with HRU

2.4 Raw Material Procurement and Preparation

The testing of the dryer was conducted using the PTS-10 variety of turmeric (*Curcuma longa*) as this variety is grown in large quantity in Erode and other areas of Tamilnadu. Turmeric were procured directly from famer at Erode and washed thoroughly in a turmeric washer using tap water at normal temperature to remove the adhering extraneous matter then it was boiled in a turmeric steam boiler for 5min to achieve softening of the produce and afterwards it was dried in the developed dryer.

2.5 Condition of Operating the dryer

In the process for determining the efficiency of the dryer, different operating conditions were used. Table 1 shows the operation temperatures and inlet air velocity at which efficiency of the dryer was determined.

Table 1: Description of operating conditions for drying runs

	Air velocity (m/s)	Temp (°C)	Description	Parameters determined
C-I (Without HRU)	1.5	60, 65, 70	Exhaust air vented into the atmosphere	- Heat utilization factor of turmeric - Overall thermal efficiency - Specific energy consumption - Drying characteristics of turmeric - Economy analysis of the dryer
C-II (With HRU)	1.5	60, 65, 70	Energy in exhaust air recovered using Heat recovery unit.	

2.6 Performance Evaluation

Experiments were conducted to evaluate the performance of the drier. First idle run test was conducted on the dryer with heat recovery unit (pre-heating), the heater was switch on with the thermostat set using optimum drying temperature of 65^{0}C (Gursewak *et al*., 2010) and the blower was operated at the rated speed but the inlet chute of the blower was adjusted to create four selected air velocities of 1, 1.5, 2, 2.5m/s. Data generated from the preliminary studies were used to determine the air velocity having the best heat recovery efficiency of the HRU. The parameters measured and recorded includes the come up time, air flow rate and temperature into and out of the heat exchanger (cold and hot stream), and the external temperature of the drying chamber.

Drying runs were performed on the dryer by drying of steamed-boiled turmeric rhizomes according to the conditions of drying operations as presented in Table 1. Temperature and relative humidity of the drying chamber was measure using data logger (Equinox® EQ-171). The performance of the dryer was evaluated in terms of drying efficiency (η_d), heat utilization factor (HUF), Temperature transfer efficiency (TT_E) and overall thermal efficiency (η_{th}). These were estimated by the method adopted by Sahay and Singh (2001) as discussed below.

1) Drying efficiency, η_d

Drying efficiency is defined as the ratio of the energy utilized for heating the sample for moisture evaporation to the total consumed energy (Vieira *et al*., 2007). Sensible heat of drying air was considered as being the effective heat for drying; therefore, drying efficiency is mathematically defined as follows

$$\eta_d = \frac{T_d - T_E}{T_d - T_{dw}} \tag{16}$$

T_d = dry bulb temperature of the heated air, °C
T_e = dry bulb temp of the exhaust air,°C
T_{dw} = wet bulb temperature of the heated air, °C

The dry bulb temperature of the heated and exhaust air for each trial was measured using mercury-in-glass thermometer of 0-150^{0}C range and Equinox data logger. The wet bulb temperature of the exhaust air was determined from the psychrometric chart using dry bulb temperature and relative humidity.

2) Heat utilization factor, HUF

Heat utilization factor is defined as the ratio of heat utilized by the turmeric to heat supplied by the hot air (Sahay and Singh 2001).

$$HUF = \frac{Dropindrybulbtemperatureofdryingair}{Increaseindrybulbtempertureofambientair}$$

$$= (T_d - T_e)/(T_d - T_{c1}) \quad (17)$$

3) Overall thermal efficiency η_{th}

Overall thermal efficiency (η_{th}) is the ratio of energy required to evaporate moisture and the energy supplied to the dryer and it can be calculated according to equation (18), (Toneli, 2013).

$$\eta_{th} = \frac{M_W \Delta H}{M C_{pa}(T_d - T_a)} \quad (18)$$

M_w=Water evaporation flow (kgs^{-1}),
ΔH =vaporization enthalpy (kJkg^{-1}),
M = Air mass flow (kgs^{-1}),
C_{pa}= specific heat of air (kJkg^{-1}°C^{-1}),
T_d and T_a are the absolute temperature of the drying and ambient air respectively.

4) Specific energy consumption

According to Ashok, (2014) another method to estimate the energy efficiency of a drying system is to calculate its specific energy consumption. It is the amount of energy used in removing one kg of moisture from a food material in kWh/kg

5) Drying rate

The duration of the drying process is the most important parameter to be considered in evaluating a dryer. It is estimated from the time when the dryer is loaded with fresh product until when the product dries to the required moisture level, usually given as hours or days. Drying rate was calculated using equation (19)

$$k = W_L/t \quad (19)$$

k = Drying rate, kg/h
W_L= amount of moisture evaporated, kg
t = time, h

2.7 Economic Analysis

Drying operation as a commercial enterprise requires cost analysis of the process to prove its economic viability (Krokida *et al.,* 2004). The Cost analysis that was conducted to determine if the expenses of installing and operating a waste heat recovery system is justified is the Return on Investment (ROI) analysis (Gene, 2002). The main aim of understanding ROI of a particular process is to identify if the process generates profit or loss.

Return on investment analysis was carried out according to (Raghavendra, 2010) and is given by.

$$ROI = S/C_{eq} \tag{20}$$

Where

C_{eq} = Additional equipment cost

S = Annual Savings and is given by,

$$S = [C_{ea}] - [TAC] + [C_{et}] \tag{21}$$

where:

TAC = Total annual cost

C_{ea} = Annual costs from electrical energy = $C_e \times t_i$

C_{et} = Savings from the energy reduced through shorter drying time.

$$C_{et} = C_e \times t_s \tag{22}$$

t_s = Time saved due to shorter drying times (hr)

C_e = Cost of kWh of electricity consumed per hour

t_i= Annual operation time. (hr)

Total annual cost when the system is operated in C-I *or C-II is given by* (Raghavendra, 2010),

$$TAC = e\,(C_{eq}) + C_{op} \tag{23}$$

where:

e = depreciation and is given by (Raghavendra, 2010),

$$e = [i_r(1 + i_r)^L]/[(1 + i_r)^L - 1] \tag{24}$$

For C-II,

C_{eq}= Additional equipment cost = Cost of HRU + Cost of air recirculation ducts

C_{op} = Operation Cost (Electricity) (Rupee/kWh)

i_r = Interest rate

L = Life span of equipment.

The cost analysis was calculated based on the drying time of the product and the total energy utilized in the drying process at different conditions. Annual return on investment (ROI) was calculated considering average of 10 working hours per day and 260 working days or 130 batch drying operation per annum with one drying cycle per two working days. The kWh cost of electricity was taken as indicated by Tamil Nādu Electricity Regulation Commission (TNERC).

A cost of 5.75 rupees per unit electricity was selected for this calculation. Assuming the number of batches of drying operation in a year is 130, the cost of operation is shown on Table 2 and the cost of additional equipment in Indian rupee is shown in Table 3

Table 2: Cost of Operation (Electricity)

Condition	65°C (C-I)	65°C(C-II)
Drying time/batch (h)	24	20
Batch per year	130	130
Hrs per year	3120	2600
Energy consumed per batch (kWh)	35.2	28
Energy consumer per year (kWh)	4576	3640
Electricity cost per year (Rs)	26312	20930

Table 3: Cost of Addition Equipment (HRU)

S/N	Material	Quantity	Price/unit (Rs)	Cost (Rs)
1	Mild steel plate	$2.1m^2$	$560/m^2$	1176
2	Aluminium sheet	$1m^2$	$460/m^2$	460
3	PVC pipe	2m	$315/m^2$	630
4	PVC elbow	2	180	360
5	Workmanship	-		5000
	Total			**7626**

1) Return on Investment

i_r = Interest Rate = 7%

L = Lifetime of equipment = 20 years

Therefore, e = $[0.07(1+0.07)^{20}] / [(1+0.07)^{20} - 1] = 0.0944$

For Condition (C-II),

C_{eq} = Equipment cost

= Cost of Heat Recovery Unit + Cost of Recycle ducts =Rs 7,626

Cost of operation, C_{op} = Cost of electricity used for the process

Total Annual Cost for C-II, 65°C = $(0.0944 \times 7626) + 20930 = 21650$ rupees

Annual savings S, due to energy reduced through shorter drying time and more effective heat utilization = 26312 - 21650 = 4662 rupees

Return over investment = S/C_{eq}

= 4662/7626

ROI = 0.6114

This procedure was repeated for comparing C-I and C-II for drying temperature of 60 and 70°C and ROI calculated were 0.6207 and 0.5965. Therefore, average value of ROI is 0.61.

3. Results and Discussion

Drying runs at operating conditions of C-I and C-II were conducted and observations are stated and discussed below.

3.1 Effect of HRU on drying efficiency

HRU was observed to increase drying efficiency of the dryer at all temperatures. The mean drying efficiency of the dryer was increased from 0.263 to 0.413 at 60°C, 0.240 to 0.423 at 65°C and 0.196 to 0.363 at 70°C as shown in Table 4 and expressed in Figure 5. It was also observed that there was decrease in drying efficiency at 70°C. As discussed by (Sahay and Singh, 2001), this may be due to the fact that there is no increase in moisture diffusion within the produce to correspond to the increase in heat energy available. The result showed significant different ($P<0.05$) between C-I and C-II and the test data and ANOVA for both C-I and C-II is given in Table 4 and Table 5 respectively.

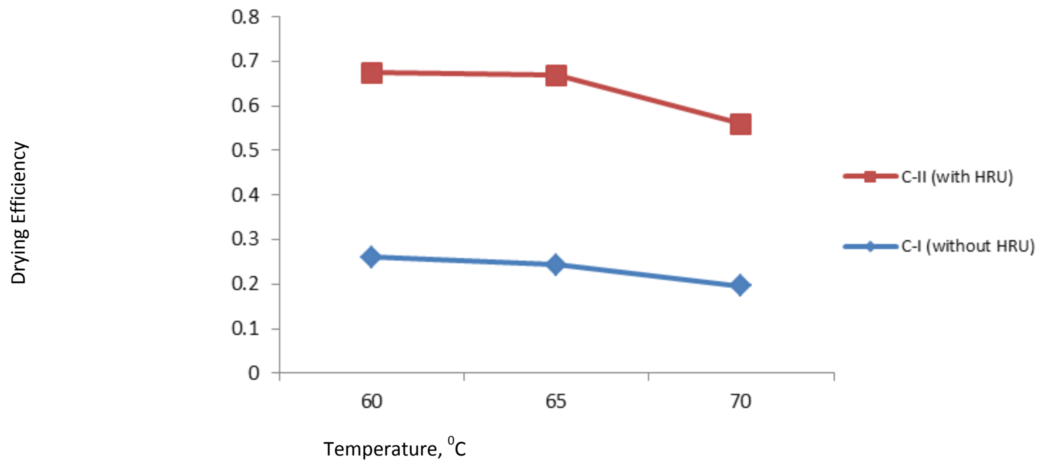

Figure 5: Drying efficiency at different operating conditions

Table 4: Mean Tables of Drying Efficiency

	T1	T2	T3
C-I	0.2633	0.2400	0.1967
C-II	0.4133	0.4233	0.3633

Table 5: ANOVA for Effect on Operating Conditions on Drying Efficiency

Source	df	SS	MS	F	PROB
TOT		17	0.14640	0.0086	12.4009
Trt	5	0.1380	0.0276	39.7632	0.452 NS
Err	12	0.00833	0.0006	1.0000	
C	1	0.12500	0.1250	180.000	0.000 **
T	2	0.01223	0.0061	8.8080	0.102 NS
CT	2	0.00083	0.0004	0.6000	0.625 NS
Err	12	0.00833	0.0006	1.0000	

3.2 Effect of HRU on Heat utilization factor

HRU was observed to significantly increased heat utilization factor of the dryer at all temperatures as shown in table 6. The HUF of the dryer at all temperatures is shown in Figure 6. Sahay and Singh, (2001) stated that the ability to increase the heat utilisation factor of a drying process implies that there will be increase in the percentage of the heat supplied utilized, thus, an improvement in the thermal efficiency of the dryer. The result showed significant different ($P<0.05$)between C-I and C-II and the ANOVA for both C-I and C-II are show in Table 7

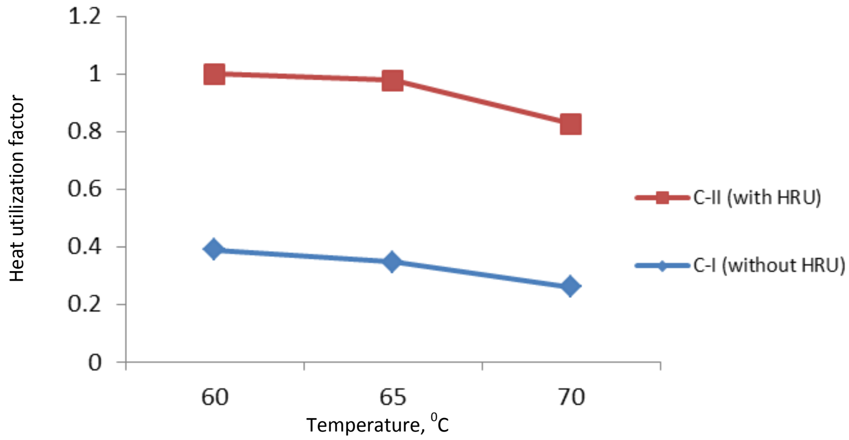

Figure 6: Heat utilization factor at different operating conditions

Table 6: Mean Tables of Heat Utilization Factor (HUF)

	T1	T2	T3
C-I	0.3933	0.3500	0.2600
C-II	0.6100	0.6300	0.5633

Table 7: ANOVA of Effect of Operating Conditions on Heat Utilization Factor (HUF)

Source	df	SS	MS	F	PROB
TOT	17	0.372511	0.021912	14.8280	
Trt	5	0.354778	0.070956	48.0150	0.439 NS
Err	12	0.017733	0.001478	1.0000	
C	1	0.320000	0.320000	216.544	0.000 **
T	2	0.028744	0.014372	9.7256	0.093 NS
CT	2	0.006033	0.003017	2.0414	0.329 NS
Err	12	0.017733	0.001478	1.0000	

3.3 Effect of operating conditions on overall thermal efficiency

HRU was observed to increased thermal efficiency of the dryer at all temperatures (table 8) and by 15% at operating temperature of 65°C. Operating temperature had no significant effect on thermal efficiency of the dryer. The overall thermal efficiency of the dryer at all temperatures was shown in Figure 7.

In an experiment conducted by (Timothy, 2011), Heat recovery ventilator was attached to a low-cost meat dehydrator and an increase in efficiency of 20% was achieved. The ANOVA result given in (Table 9) showed that there significant different ($P<0.05$) between treatments C-I and C-II. Since the HRU can be attached to any dyer with little or no modification, this means that thermal efficiency of commercially available dryers can be increased by at least 15% with investing in HRU.

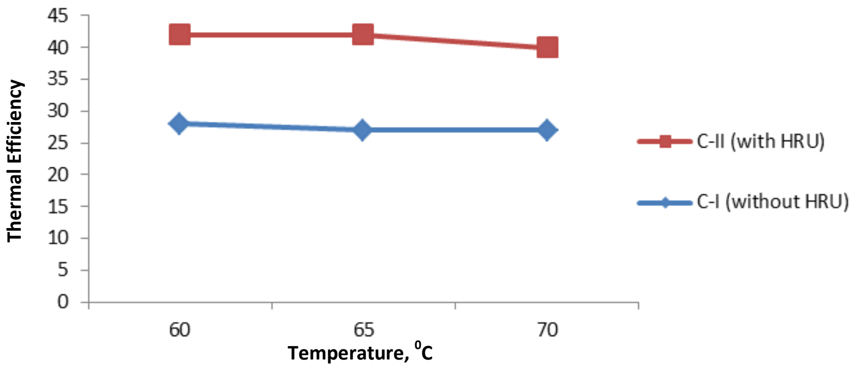

Figure 7: Overall thermal efficiencies at different operating conditions

Table 8: Mean Tables of Thermal Efficiency

	T1	T2	T3
C-I	28.0000	27.0000	26.9967
C-II	42.0000	42.0033	40.0000

Table 9: ANOVA of Effect of Operating Conditions on Thermal Efficiency

Source	df	SS	MS	F	PROB
TOT	17	986.7892	58.04642	7.3718	
Trt	5	892.3000	178.4600	22.6642	0.474 NS
Err	12	94.48913	7.874094	1.0000	
C	1	882.2800	882.2800	112.0484	0.000 **
T	2	7.020033	3.510017	0.4458	0.692 NS
CT	2	3.000011	1.500006	0.1905	0.840 NS
Err	12	94.48913	7.874094	1.0000	

3.4 Effect of operating conditions on specific energy consumption

The specific energy consumption of the dryer at all temperatures decreased with HRU. The specific energy consumption of the dryer at all temperatures was shown in Figure 8. The test data for both C-I and C-II is given in Table 10.

Table 10: Specific Energy Consumption at Different Operating Conditions

Operating condition		Energy used (kWh)	Mass of water removed (kg)	Specific energy consumption (kWh/kg|)
C-I, T_1	Without HRU and at 60°C	35.2	14.8	2.38
C-I, T_2	Without HRU and at 65°C	35.3	15.4	2.30
C-I, T_3	Without HRU and at 70°C	32.3	14.8	2.18
C-II, T_1	With HRU and at 60°C	29.7	15.3	1.94
C-II, T_2	With HRU and at 65°C	27.0	15.1	1.79
C-II, T_3	With HRU and at 70°C	27.0	14.9	1.80

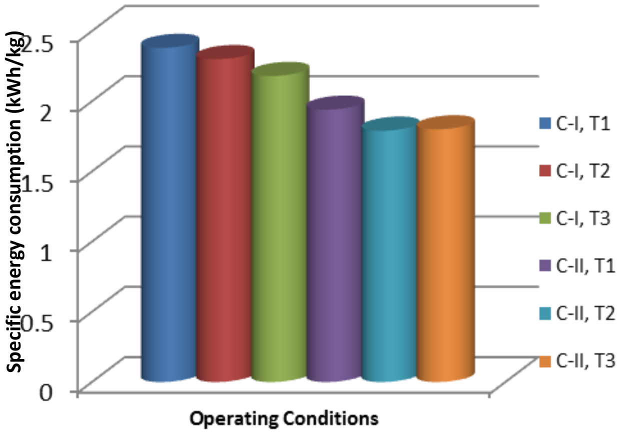

Figure 8: Specific energy consumption at different operating conditions

3.5 Effect of Operating Condition on Drying Rate

The drying rate of turmeric inside the dryer at the different operating condition C-I and C-II is shown in the Figure 9 and 10 respectively. Temperature showed effect on drying rate, but no trend was observed with 'with' or 'with-out' HRU on rate of drying as shown.

Drying was observed to occur mainly at falling rate period and also it was observed that samples in C-II reached safe moisture range before samples in C-I at all temperature levels of T_1, T_2 and T_3 that is 60°C, 65°C and 70°C respectively therefore drying time for samples in C-II were shorter.

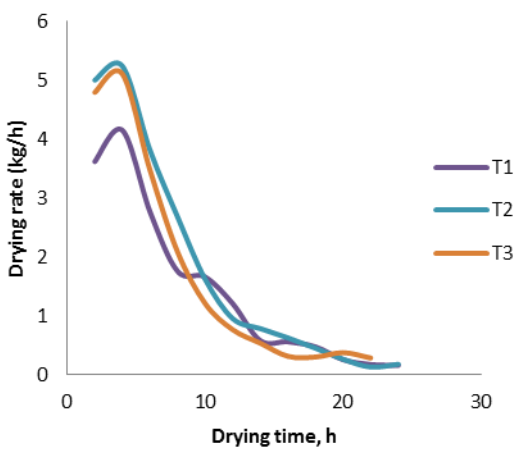	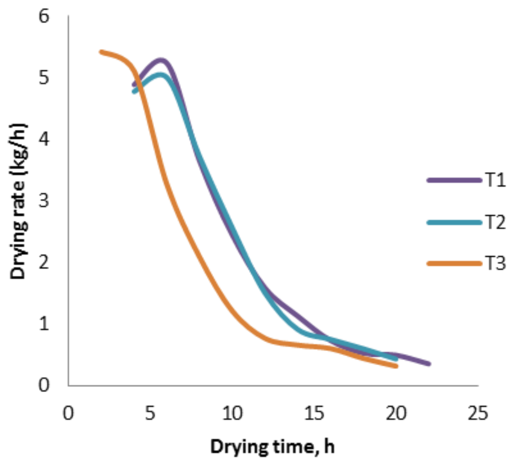
Figure 9: Drying rate at C-I operating condition	Figure 10: Drying rate at C-II operating condition

3.6 Cost Analysis

1) Return of Investment

The calculated Return-On-Investment for C-II, at drying temperature of 65°Cis 0.6114. The procedure used to calculate ROI for C-II, 65°C was repeated to calculate C-II for drying temperature of 60°C and 70°C and ROI calculated were 0.6207 and 0.5965 respectively. Therefore average value of ROI is 0.61.

2) Payback Period

The calculated payback period is approximately 19months, therefore it can be said that investing in the Heat recovery unit with a lifespan of 30 to 50 years is a profitable investment.**4.**

Conclusion

A flatbed dryer with a heat reclamation system was developed. Evaluation of the dryer was carried out with ‘No-load’ test and drying runs of turmeric at conditions C-I and C-II, indicating without and with heat-recovery-unit respectively at temperatures of 60°C, 65°C and 70°C.Thermal Efficiency of the dryer was determined, at C-I it was found to be 28, 27 and 27% at 60°C, 65°C and 70°C respectively and at C-II it was 42, 42, and 40% for 60°C, 65°C, and 70°C respectively. Effectiveness of using a HRU to recover the waste heat from the exhaust stream of the dryer was studied and found that by using C-II the overall thermal efficiency was increased at all the temperatures. 15% increase in thermal efficiency was achieved. Specific energy consumption was reduced for all levels of C-II as compared to C-I and the result shows that testing condition C-II, 65°C has the lowest value of specific energy consumption of 1.79 while C-I, 60°C has the highest value; 2.37.

Drying curves of turmeric were plotted and found that C-II performed better in drying turmeric since the moisture lose was faster than in C-I and the drying time was lower.

It was concluded that the developed flatbed dryer can be used to dry 25 kg of turmeric per batch in 25 hours drying time and C-II, 65°C showed better quality in terms of energy efficiency and drying rate.

The return on investment for HRU was found to be 0.61 and the payback period is 19 months.

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