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Investigation of Thermal and Hydraulic Performance and Characteristics of Forced Circulation Food Dryer Provided with Roughened Solar Air Heater

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Abstract The most abundant continuing energy source available to the human race is solar energy especially the electromagnetic energy emitted by the sun, while solar energy is not being used as a primary source of fuel energy at present time a large research and development effect is underway to develop economical system to harness solar energy efficiently as major source of fuel energy particularly for heating and cooling of buildings and drying agricultural farm and industrial products. Many solar systems i.e. solar air heater, solar water heater, solar crops dryer, solar cooker and solar cells have been designed, fabricated and used at present time. Solar air heaters are extensively used for space heating, artificial crop and grain drying and industrial products drying.

This paper focus on the experimental investigation on drying different farm products in solar food dryer coupled with roughened solar heater provided with different roughness to create turbulence in the flow. An extensive experimental investigation has been carried out to observe the effect of roughness and flow parameters i.e. relative roughness height (ϵ/D) and relative roughness pitch (p/ϵ), flow Reynolds number, solar intensity of radiation and different farm products (wheat, cabbage, cauliflower, and red chilli) placed over trays inside the dryer under actual out door condition. The experimental setup consist of three bell mounted ducts protected by J.D. Fan regulated with a variac to control the speed all the three ducts have been provided with valves and orifice meter to measure flow rate of air through the ducts which are attached with the dryer. The operating parameter covered the range of $10 \geq p/\epsilon \leq$ RD and $0.0145 \leq \epsilon/D \leq 0.0288$, $6000 \leq R_e \leq 18000$, solar intensity (I) = 450 to 970 w /m^2 , $\dot{m}$ = 0.015 to 0.473 kg /sec. and crops like wheat cabbage cauliflower red chillies.

The various data collected during the experimentation were: pressure difference across orifice meter with water Column U tube manometer, temperature of absorber plate with calibrated thermocouple, temperature of air in the duct and dryer with platinum. Resistance sensors, dry bulb and wet bulb temperatures in the dryer with psychrometer, solar radiation intensity with pranometer and wind speed with wind monitors. Results show that in the range of parameters investigated the values of enhance factor in the smooth and roughened solar air heater with dryer found in the range of : $\frac{\eta_R}{\eta_S}$ for collectors = 1.2 – 1.4 $\frac{\eta_R}{\eta_S}$ for dryer 1.35- 1.52 ratio of moisture transferred $\frac{\dot{m}_R}{\dot{m}_s}$ = 1.4 – 1.6

It has been also found that the ratio of increase of collector efficiency factors decreases with increasing Reynolds numbers. It has been also observed that ratio of moisture removal increase with relative roughness height (ϵ/D). It can therefore be concluded for this investigation that solar food dryer provided with artificial roughness to create turbulence in the flow could performed considerably better with respect more heat transfer and mass transfer. It is expected that increase in solar radiation intensity by providing booster mirrors can further enhance both air heater and dryer efficiency and in the same time enhance rate of heat transfer and mass transfer.

Keywords* — *Moisture, booster mirror, food dryer, pyrnometer, artificial roughness

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I. INTRODUCTION

The most abundant continuous energy source available to the human race is solar energy especially the electromagnetic rays emitted by the sun. While solar energy is not being used as a primary source of fuel energy at present time. A large research and development effort is underway to develop economical system to harness solar energy, efficiently as major source of fuel energy, particularly for heater and cooling of building and drying agricultural farms and industrial products. Many solar system like solar water heater, Solar air heater and Solar cooker and Solar cell have been designed, fabricated and used at present. Solar air heater are extensively used for space heating agricultural crops and food drying and many other systems required low grade thermal energy.

Solar drying of crops & fruits and vegetable has been practiced around the world for contained in the open air under the rays of the Sun. The traditional method of drying suffers from several problems among with certainly of drying time High labour cost, the need of large areas Infection by insects and other foreign bodies. Also died product are poor quality due to unavoidable presence of rain wind moisture and dust to use freely renewable and clean energy as a primary source provided by the Sun introduction of solar dryer in developing countries can reduce losses of crops and improve the quality of the dried products compared to traditional drying methods.

In recent years many studies have been done to develop the solar dryer to preserve agricultural products.[1,2] In order to preserve agricultural products for later use to prevent growth of fungi and bacteria over the seeds agricultural products must be dried to retain optimum quantity of moisture Solar food drier is essential The moisture content and the temperature at which the products should be dried are fixed for different agricultural products agricultural crops and food drier require low grade energy in the temp. Range of 50 °C to 75°C[3] which is easily available in solar air heater coupled with food driers. The products having large moisture content require higher drying temperature higher temperature can be obtained by making collection plate of air heater rough Roughness of collector sheet creates turbulence in the flow causing more heat transfer to air from the collector. It is expected higher mass flow of air can remove more moisture content from the agricultural products.

It is not possible to increase the loss of moisture rate with ordinary natural circulation. It is expected that providing roughness over collector sheets of air heater can enhance moisture loss. In view of very little information available on various aspects of analytical and experimental performance of solar food dryer with roughened collector sheets, this investigation into heat transfer and mass transfer characteristics has been taken up. An extensive experimental investigation has been carried out for moisture loss rate for different products like cauliflower, cabbage, chilly and wheat with roughness sheets of various roughness factors (ε/D and p/ε) at variable mass flow rate.

1.1 Performance of Solar Dryer

Drying involves both heat and mass transfer operations simultaneously and hence performance can be predicted by measuring moisture content at any time (i.e. at particular solar intensity) temperature, humidity and solar intensity.

Effects of temperature on loss of moisture content (i.e humidification of air entering into food dryer. If temperature of air leaving form air heater increases form t_A to $t_{A'}$ then loss moisture from food dryer increases from (W_B – W_A) to ($W_{B'}$ - to $W_{A'}$) per kg of dry air.

$$\dot{m}_a = \frac{\dot{m}_m}{W_2 - W_1} = \frac{m_i - m_f}{W_2 - W_1}$$

$$\int_d = \frac{\dot{m}_m}{\dot{m}_f} \times 100 = \frac{m_i - m_f}{m_i} \times 100$$

$$\eta_c = \frac{\text{Rate of the heat carried away by air in the air h}}{\text{Rate of solar energy incident}}$$

$$\eta_d = \frac{\dot{m}a \times Cpa\,(t1 - t2)}{I \times Ac}$$

$$\eta_d = \frac{\dot{m}_a \times h_{fg}}{\dot{m}_a \times Cpa \times (t_1 - t_2)}$$

$$HUF = \frac{t_1 - t_2}{t_1 - t_i} \qquad t_2 > t_i \text{ and } t_2 < t_1$$

$$COP = \frac{t_2 - t_i}{t_1 - t_i}$$

HUF+ COP = 1

Based on above principle we can increase the thermal performance of food dryer by increasing out let temperature of air from the air heater by providing roughness over collector plate. The rate of loss of moisture can be further increased by forced circulation i.e. increasing mass flow.

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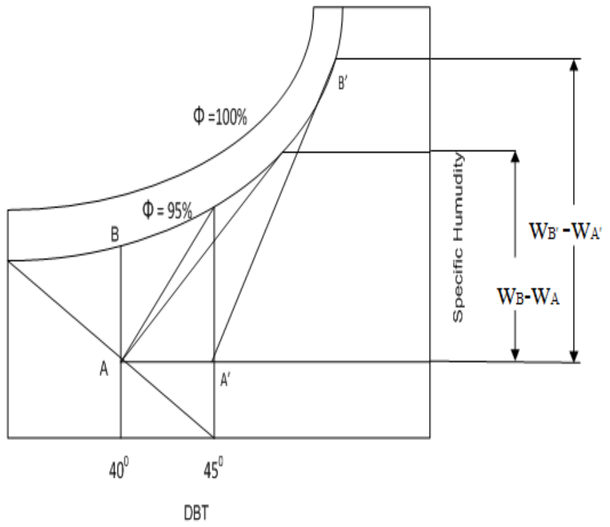

Fig 1 Specific Humidity graph

1.2 Objective of Present Investigation

Anil kumar, Renu singh, Om Prakash, Ashutosh [3] discuss solar dryer with drying characteristics analysis of the crops and highlighted different types of simple cabinet type crops dryer with natural circulation,

Hajar Essalhi Rachid Tadilin, M.N. Bargach [4] presented conception of absorber of a solar air collector indirect solar dryer of pear absorber plate in simple without forced circulation and found dryer efficiency in 11.11%.

In view of the very little information available in various aspects of analytical and experimental performance of solar food dryer with artificial roughness over collector plate, this investigation into heat transfer and mass transfer characteristics has been taken up.

An extensive experimental investigation has been carried out for moisture loss rate for products like cauliflower, cabbage, chilly and wheat with variable roughness (ε/D) and P/ε) at variable mass flow rate of air into solar air heater and solar food dryer. Both heat and mass transfer increases with increase in Reynolds number and if roughness near the collector plate is more than the laminar sublayer thickness, convective heat transfer from the plate to air increases.

The experimental setup consists of bell mounted solar air heater duct made of kit-ply, coupled with a cabinet and a chimney, copper wire of different diameters on the absorber plates fixed at the varying pitch provided artificial roughness.

II. Experimental System Development

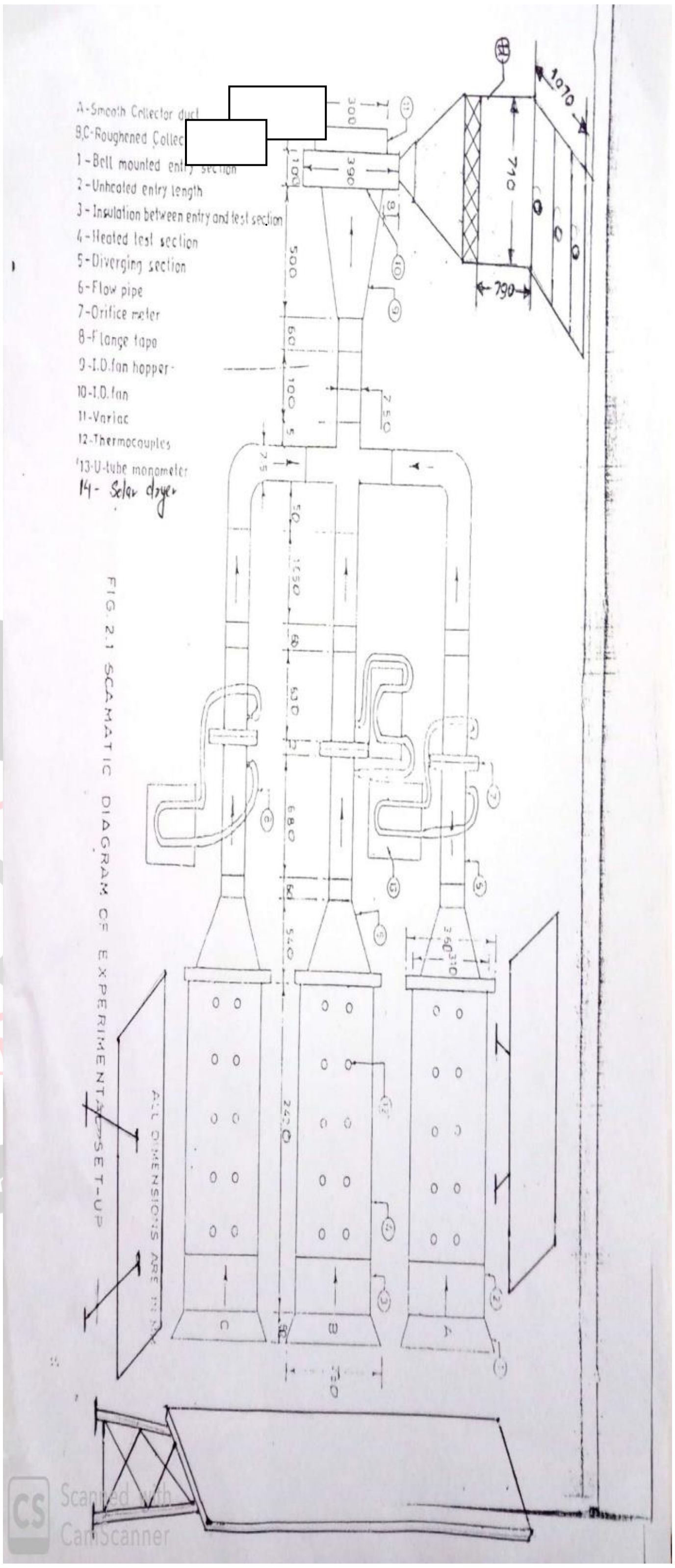

Fig 2 shows the schematic diagram of the experimental setup developed and used. The system for solar food dryer consists of the following main components.

2.1 Solar Air Heater Duct

The duct is provided to admit suction air through bell shaped mouth into the cabinet dryers Three ducts were used one having smooth absorber plate and other products having two different roughness on the absorb plate. Air gap of 25

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mm provided between the bottom and absorber plates for each duet resulted in a cross section of 250mm x 25mm each.

2.2 Absorber Plate and Cover Plate

Dull black painted 20 SWG aluminium sheets of 1.84 m length and 28 cm width were used. Out of 28 cm width, 25 cm formed clear absorber width while 1.5 cm on each side rests on wooded support. Artificial roughness was produced by embedding circular copper wires of different gauges on back side of the absorber plates.

2.3 Cabinet Dryer

The cabinet contains the drying and forms a part of air heater. The cabinet and air heater duct joined together so that no hot air leaving any ducts leaked net of cabinet two trays are provided of each dimension 88cm x 24cm x 6 cm with bottom as fine net of wires are provided. The hot air from air heater passes through the food product placed over the trays.

2.4 Flow Control Arrangement

Air flow rate through the duct was controlled by means of three phase varied connected in series with the ID fan. Voltage regulation of the varied provided constant supply of power to run the motor of the ID fan speed. Constant mass flow rate was maintains through the three ducts in inspite of variation of out site voltage.

III. INSTRUMENTATION AND SYSTEM ADJUSTMENT

Instrumentation plays a vital role in any experiment.

Investigation special care was taken to make the measuring instrument more sensitive to record the data very accurately. The salient features of the apparatus used for instrumentation are:

3.1 Air Flow Measurement

Air flow measurement was accomplished by three identical orifice meters one of each duct system All the three orifice meter were flanged tap type which were designed fabricated calibrated and fitted in the 3" diameter pipe. Orifice meter were calibrated using Pitot tube to determine coefficient of discharge. The pressure difference was measured with U tube manometer filled with water.

3.2 Temperature Measurement

26SWG calibrated copper constant a thermocouple had been used to measured local temperature of absorbers plates. These were embedded on tips of side of absorber plate. The temperature of air as flows progress through solar air heater was measured with the helps 48 channel data hogger having 100 platinum resistance props. Ambient air temperature was measured using standard Mercury thermometer with least count 0.1 °C.

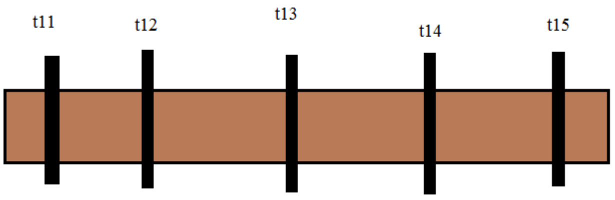

Fig 3 Thermocouple in air ducts to measure air flow temperature

3.3 Solar Radiation in Intensity Measurement

Intensity of global solar radiation was measured by pyranometer having a Calibration factor of 5.8 MV / Cal/ cm^2/min. The signal from pyranometer was fed to a digital mili-voltmeter. The reading of digital mili-voltmeter were recorded in mili-volt with a least count of 01mv, would then be converted to intensity of radiation in terms of W/m^2 (1mv =129.3W/m^2)

3.4 Wind Speed Measurement

Wind speed was measured with the help of a wind monitor which provides wind speed in Km/hr.

3.5 Pressure Drop Measurement across Orifice meter

The pressure difference across the three orifice meter was measured by U tube manometer fitted in each pipe connected in each duct.

3.6 Humidity Measurement

The instrument used to measure the specific humidity in psychrometer. It consists of dry bulb thermometer and wet bulb thermometer. Both of them are mounted on a suitable plate having arrangement for continuous supply of distilled water to keep the width wet on the bulb of wet bulb thermometer.

3.7 Weight loss of moisture measurement

Loss of moisture was measured by weighing the wet food product and dry food product with the digital sensitive balance. Weight of product was taken at the interval of 60 minutes.

IV. EXPERIMENTATION AND DATA COLLECTION

4.1. The experimental setup developed and tested for rediness has been put under experimentation and types of product investigated in the experiment and data's were collected.

4.2. Types of product tested and range of solar intensity

1.Cabbage

2.wheat

Range of solar intensity (490 to 900W/m^2)

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4.3. Test data were collected at the interval of 1 hour on each day between 9AM to 2PM

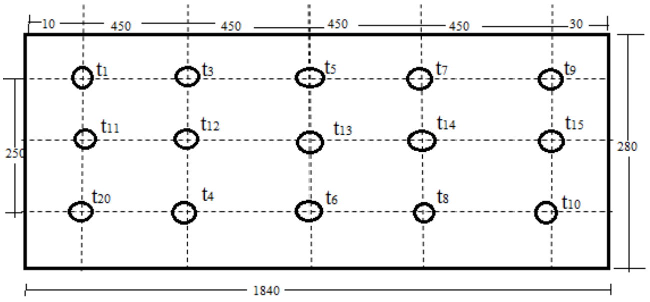

Fig 4 - Absorber plate with thermocouples to measure plates temperature.

POTENTIOMETER & THERMOMETER READING

SL NO	TIME(HOUR)	SOLAR INTENSITY		THERMOMETER READING(°C)
		m.v.	W/m²	
1	9.00AM	4.65	601.245	32
2	10.00AM	5.02	650	33
3	11.00AM	5.50	711.15	33
4	12.00NOON	5.98	733.21	35.5
5	1.00PM	4.87	691.75	34
6	2.00PM	4.57	590	34

Table 1 -Dryer Temperature and inlet and outlet temperature

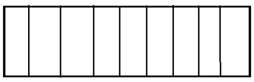

Fig 5 – thermocouple in air ducts to measure air flow temperature.

Time	t_i	t_{16}	t_{17}	t_{18}	t_{19}	t_{20}	t_i	W_i	t_o	W_o	ΔW
10AM	S	39	39.5	40.1	41	42	38.6	0.0154	42.7	0.0176	0.022
	R_1	40	41	42.5	43	43.4	42	0.0178	43.5	0.0209	0.024
	R_2	41.5	42	42.8	43.5	45	42.5	0.0181	44.4	0.0225	0.044
11AM	S	39	40.4	41	41.8	42	39	0.0155	42	0.0175	0.0020
	R_1	40	41.5	42.6	43.5	44	40	0.0156	42.8	0.0182	0.0026
	R_2	43	44.4	45.4	45.8	44	43	0.0155	46.5	0.0195	0.0043

Table 2 -Temperature and specific humidity variation inside the food dryer.

Sl. no	Time	TYPe	t_1	t_2	t_3	t_4	t_5	t_6	t_7	t_8	t_9	t_{10}	t_{11}	t_{12}	t_{13}	t_{14}	t_{15}	Δt	t_p	t_f
1	9	S	38.2	39.1	49	52.1	53	54.5	56.1	57.3	59	60.1	33.3	34	34.5	35.5	36.5	3	51.4	34.8
		R1	36.2	37.3	42	46.2	49.7	49.4	45.2	52.5	53.6	55.5	33	34.5	35	36.5	37.5	4.5	47.32	35.2
		R2	36.5	37.6	42.5	46.7	50.1	50.6	45.7	52.9	53.7	55.8	33.5	34.9	35.4	36.9	37.9	4.4	47.2	35.7
2	10	S	41.5	42	52.8	47.1	55.1	58	58.5	58.6	59	60.2	34	35.5	36.1	36.5	37	4	53.3	35.8
		R1	36.9	38	44.1	55.2	51.5	53.5	54.5	55.4	56	56.5	34.1	36.3	37	38.5	39.8	5.5	55.85	37.1
		R2	37.2	38.3	44.5	55.7	51.7	53.7	54.9	55.9	56.7	56.8	34.6	36.9	37.3	38.9	40.3	5.7	55.9	37.6
3	11	S	42.1	43	54	48.1	56.5	57.5	58.7	59	61.5	62	35.2	35.5	36	37.2	38	2.8	54.24	36.3
		R1	37.5	38.8	45.4	55.4	52	54.1	55	56	58	58.5	35.3	35.5	37.8	39.3	40.3	5	51.07	45.8
		R2	37.9	39.2	45.9	55.8	52.6	54.8	55.6	56.3	58.4	58.9	35.6	35.7	38.2	40.2	40.6	5.1	51.9	56.1
4	12	S	42.5	44	54.9	44.2	58	59	60	61	62	63.1	35	37.5	37.1	37.8	40	5	56.07	37.4
		R1	38.4	39	46	40.1	52.5	54	56	57.5	58.5	59	36	36.5	37.8	38.2	39	3	50.1	37.5
		R2	38.8	39.5	46.3	40.5	52.6	54.3	56.8	57.6	58.9	59.4	36.5	36.9	37.9	38.6	39.5	2.9	50.6	37.6

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5	13	S	46.4	42.6	56.1	54	57.2	58.5	60	62	62.5	63	37	38	39	39.2	41.2	4.2	56.63	38.5
		R1	40.2	43.5	45	54	56.1	57.1	57.5	58.1	59	59.5	37.1	38.5	39.2	40.2	41	3.9	53.3	38.9
		R2	40.6	43.9	45.4	54.3	56.5	57.6	57.9	58.3	59.4	59.8	37.5	38.6	39.6	40.7	41.6	4	53.3	39.6
6	14	S	47	48.5	57.1	58.5	59	59.5	60	62.5	63	63.5	37.6	39.4	40.4	41	41.6	4	57.86	40.4
		R1	41.6	43.8	48.9	54	56	57	58	58.5	59.5	60.1	37.5	40.1	40.8	41.5	42	4.5	53.74	40.4
		R2	41.9	44.2	49.3	54.4	56.6	57.8	58.3	58.9	60.1	60.8	38.1	40.6	41.2	41.9	42.3	4.2	54.23	40.8
7	15	S	42.4	49	57.1	58.6	60.5	59	60.1	60.5	62	62.5	37.6	41.5	42.5	42.3	42.8	5.2	57.2	40.6
		R1	41.9	44	51.5	55.5	56.5	58	58.4	59	59.6	60.4	37.9	42	42.5	43	43.6	5.7	54.5	41.2
		R2	42.3	44.5	52.1	55.9	57	58.5	58.9	60.6	60.9	61	38.1	42.4	42.9	43.6	43.8	5.7	55.2	42.2

Table 3- Time and absorber plate and air temperature at different point of air heater.

V. RESULTS ANALYSIS

Experimental data c0.0226ollected simultaneously for a smooth and roughened solar air heater coupled with crops dr0.0175yer have been represented graphically.

Experimental Results

Fig5 shows variation of ambient temperature and solar radiation intensity with time and fig5 indicates variation of wind velocity.

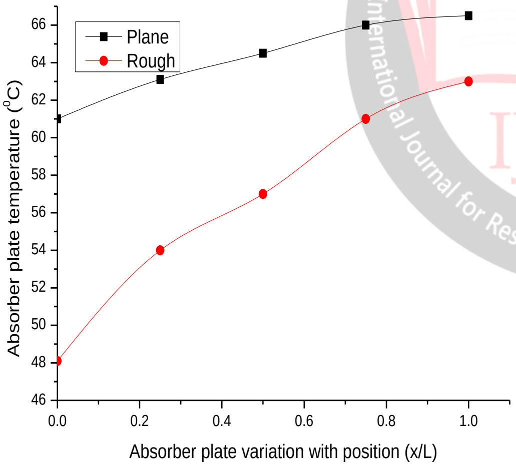

Fig6 shows collector plate temperature distribution at various points down the flow as a function of dimensionless length(X/L) for both smooth and roughened collector for mass flow rate of 0.386kg/s and roughness pitch p/ε=20 and roughness factor ε/D=0.017 and intensity of solar radiation I= 801W/m^2.

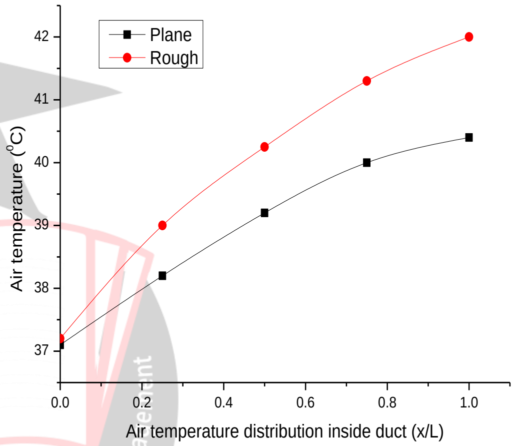

Fig7 indicates air temperature variation as a function of dimensionless length(X/L) for both smooth and roughened collector.

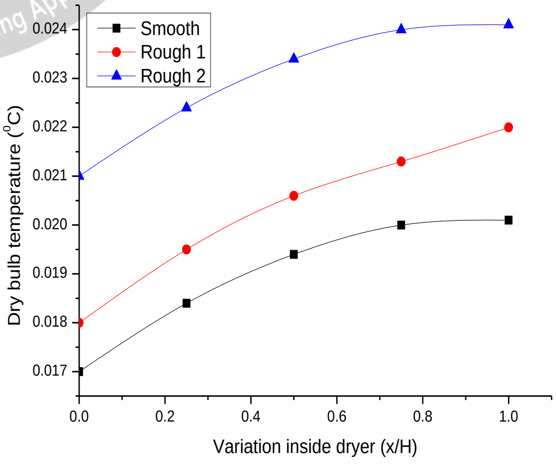

Fig8 shows temperature variation at different height of inside crops dryer.

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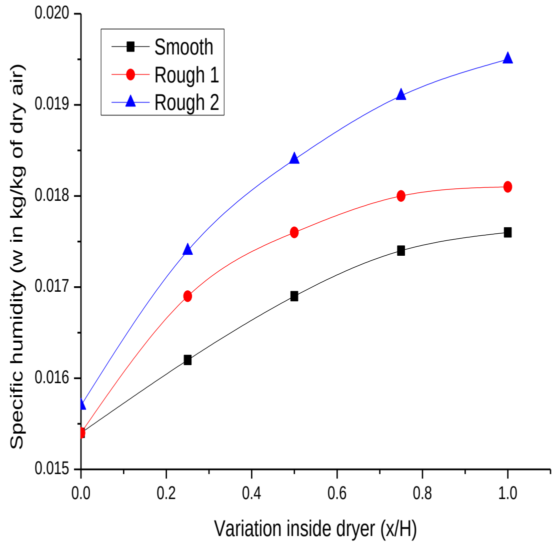

Fig9 shows variation of specific humidity inside the duct at different location.

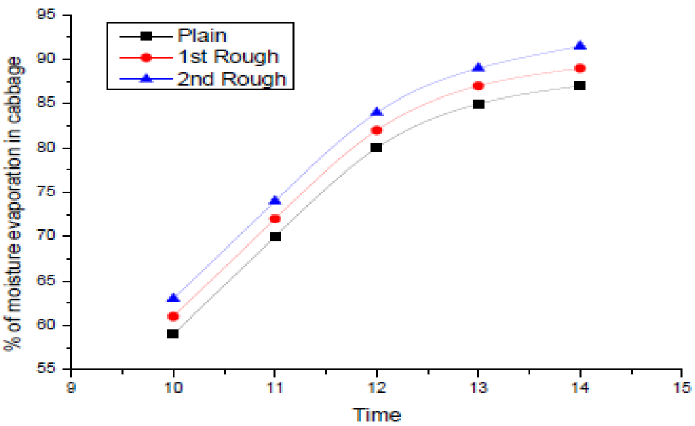

Fig10 indicates percentage of moisture evaporation with time for smooth and roughened collector for cabbage.

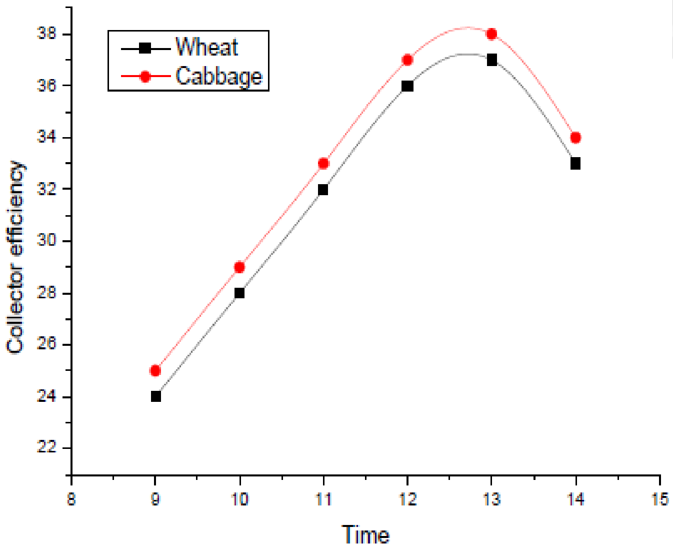

Fig11 indicates collector efficiency with time for smooth and roughened collector.

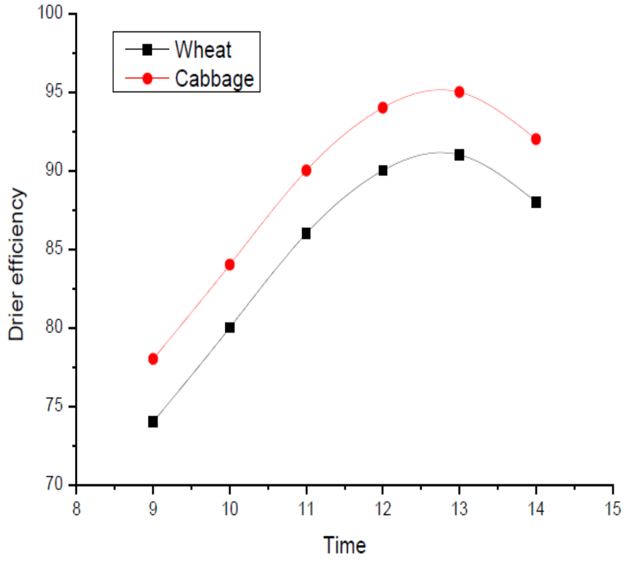

Fig12 indicates dryer efficiency with time for wheat and cabbage.

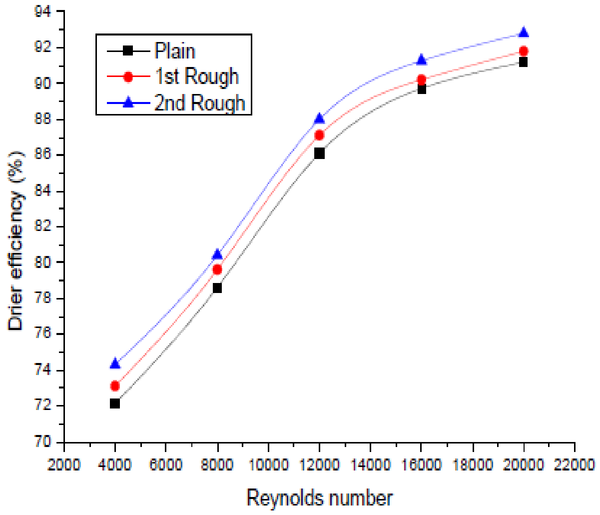

Fig13 indicates efficiency versus Reynolds no.

VI. DISCUSSION ON RESULTS

The various experimental results for smooth and roughened solar air heater attached with crops dryer have been represented. These experimental results have been utilized and workout for values of collector performance parameters (plate temperature, air temperature and efficiency) and performance of dryer (temperature, humidity and efficiency) with solar intensity, time and different roughness factors.

6.1. Effect of Relative Roughness Height (ε/D) on the performance of solar air heater

6.1.1. Effect of relative roughness height (ε/D) on the absorber plate temperature (t_p)

Fig 6 shows the typical effect of roughness factor on plate temperature. There is a remarkable effect of roughness factor (ε/D) on the plate temperature. It is observed that plate temperature decreases due to creating turbulence in the flow which enhances more heat transfer from the absorber plate to air entering into the duct. For example, for

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given values of flow parameter there has been decrease in plate temperature about 15% compared to smooth collector plate. This percentage decrease of temperature increase with increasing roughness factor (ε/D).

6.1.2. Effect of relative roughness height (ε/D) on increase in rise of air temperature in the duct

Fig 7 represents variation of air temperature at various positions of air duct. It shows that air temperature rises in the direction of flow but rise in air temperature is slower near outlet than near inlet. It is also observed that rise in temperature of air(Δt_a) is much more in rough collector duct than in smooth collector plate which indicates roughened collector absorber plate is more efficient than smooth collector plate. The increase in air temperature increases with increasing surface roughness factor (ε/D).

6.1.3. Effect of relative roughness height (ε/D) on efficiency of solar air heater

Fig 8 shows variation of efficiency of solar air heater with relative roughness height (ε/D). It is observed that efficiency of roughened solar air heater is more than smooth air heater. This is due to increase in heat transfer from absorber plate to air due to more turbulence in the flow. Higher the roughness factor (ε/D), higher is efficiency. Thermal efficiency of roughened solar air heater are found to be 42%, 46.5% and 51.5% for ε/D relative roughness height 0.0145, 0.0220 and 0.0288 respectively as compared to thermal efficiency of smooth air heater as 28.5%.

6.2.4. Effect of relative roughness height (ε/D) on temperature variation in the crops/food dryer

Fig 9 shows temperature variation with time inside the crops dryer. It is observed that temperature inside the dryer increases with time. However, increase is gradual as increasing time. It is concluded that increase in air temperature indicates higher moisture transfer from crops to air passing through crops dryer.

6.2.5. Effect of relative roughness height (ε/D) on dryer efficiency

Fig 12 shows variation of dryer efficiency with time for smooth and roughened solar air heater duct coupled with dryer. It indicates dryer efficiency is higher in case of roughened solar air heater. It is also observed that as relative roughness height increases, dryer efficiency also increases. It is further observed that rate of moisture transfer from crops having higher initial moisture is more than the crops having lower initial moisture content.

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