Study on Performance Evaluation of Forced Convection Solar Dryer for Turmeric (Curcuma Longa L.)

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Abstract

Use of non-renewable energy sources for drying of agricultural products is an expensive process at rural scale. Drying for agricultural products are one of the most attractive and cost effective application of solar energy. Therefore an appropriate technology for drying of agricultural products has been developed and its performance for drying of turmeric rhizomes has been evaluated. A forced convection solar dryer was developed. The system is capable of generating an adequate and continuous flow of hot air temperature between 55-60^{0}C. The turmeric rhizomes were successfully dried in the developed solar dryer. Turmeric rhizomes were dried with pretreatment (boiling in water for 30 min). Experimentation was carried out on boiled turmeric rhizomes with forced convection and with natural convection in the same set up. The experimental analysis showed that the natural convection solar drying takes 8 days (considering 9 sunshine hours from 10am to 6pm). Whereas forced convection drying required 6 days (considering 9 sunshine hours from 10am to 6pm) for drying of turmeric rhizomes. It is observed that turmeric dried in solar dryers take lesser time to reach the safe level of moisture content for storage when compared to open sun drying and the quality of turmeric produced are far more superior.

Keywords: Solar Dryer, Turmeric, Performance

I. Introduction

Drying is an essential process for preservation of agricultural products. Traditionally all agricultural crops were dried in open sun drying. Sun drying offers a cheap method of drying but often results to inferior quality of products due to its dependence of weather conditions and vulnerably to the attack of dust, dirt, rains, insects, pests and micro-organism [1]. Solar drying is an alternative which offers several advantages over the traditional method and it has been developed for various agricultural products. [2,3]. In natural convection solar dryers, the air flow is due to buoyancy-induced air pressure, while in forced convection solar dryers the air flow is provided by using a blower or fan operated by electricity. Drying of agricultural crops can extend shelf life of the product and improve quality also. Drying of food products reduces the post-harvest losses and reduces the goods transportation cost as most of the water is removed from the product during the drying process [4]. Food problems arise in most of the countries due to inability to preserve food surpluses rather than due to low production.

Sun shines in India over an average of 3000-3200 hr/year, delivering about 2000 kWh/m^2-year of solar radiation on horizontal surfaces [5]. This abundantly available solar energy can be used for drying of agricultural products. Although for commercial production of raisins, the forced convection solar dryer provides better control of required drying air conditions, the natural convection solar dryer does not require any other energy during operation [6]. A quantitative understanding of drying process is of great practical and economic importance. Understanding of fundamentals and mechanisms, and distribution of moisture and temperature within the product are crucial factors for the design process [7]. A wide variety of designs for solar dryers have been developed which can be categorized into direct, indirect and specialized solar dryers [8-11]. Open sun drying requires large floor area and also dependent on availability of solar energy, more than 75% of food is being produced by small farmers. These farmers dry food products by natural sun drying as solar energy is available abundantly at free of cost. Natural sun drying under hostile climate condition can cause adverse effect to quality of food product to be dried. Conventional fuel operated dryers are more energy consuming and they are costly for rural farmers, therefore need is to be use renewable energy sources as much as possible. Solar dryers are now being extensively used since they are better and energy efficient one.

A. *Solar Drying:*

Drying is a simple process of moisture removal from a product in order to reach the desired moisture content and is an energy intensive operation. The prime objective of drying apart from extended storage life can also be quality enhancement, ease of handling, further processing and sanitation and is probably the oldest method of food preservation practiced by humankind. Drying involves the application of heat to vaporize moisture and some means of removing water vapor after its separation from the food products. It is thus a combined and simultaneous heat and mass transfer operation for which energy must be supplied. The removal of moisture prevents the growth and reproduction of microorganisms like bacteria, yeasts and molds causing decay and minimizes many of the moisture-mediated deteriorative reactions. It brings about substantial reduction in weight and volume, minimizing packing, storage, and transportation costs and enables storability of the product under ambient temperatures.

II. DESIGN AND DEVELOPMENT OF SOLAR DRYER


Fig. 2.1: Overview of solar dryer

A forced convection solar dryer consists of a solar flat plate air heater, centrifugal blower, reducer flexible connector and a supporting stand. The solar air heater consists of an absorber (painted black) glass cover. The air duct beneath the absorber was made from an aluminium sheet (0.91 mm thick and 1m × 0.7m × 0.12m in size) through which air was passed. The toughened glass plate (4 mm thick, 1m ×0.6 m in size) was fixed on the frame of the absorber surface. The glass was fitted to the frame along with the help of galvanized iron angles and screws. For connecting the collector outlet to the inlet of dryer chamber, a connector made from special fibre reinforced plastic pipe (stable up to 200°C) was provided. The inlet and outlet ends of the connector were made by using two rectangular cross-sectional ducts. Centrifugal blower was used to force the air through solar air heater, at the outlet section of blower orifice meter is fitted with manometer arrangement to measure the air flow rate through the blower outlet and flat plate solar air heater inlet.

The reducer was used to connect the outlet of the blower to inlet of solar air heater with reinforced plastic pipe and collector outlet to inlet of drying chamber by reinforced plastic pipe. The cross section of the reducer was increased gradually from inlet to outlet, which helps in maintaining the uniform distribution of air in the drying chamber. In the dryer cabinet, arrangement was made to keep three number of trays on which boiled turmeric rhizomes were placed.

A. *Design of drying chamber:*

The amount of moisture removed from the turmeric, Mw (kg) was calculated by using the following equation. The quantity of moisture present in a material can be represented on wet basis and expressed as percentage. About 10 gm samples were taken and kept in a convective electrical oven, which was maintained at 105 ± 1°C until constant weight has reached. The initial and final mass, Mi, and final mass, Mf, of the samples were recorded with the help of electronic balance. The moisture content, Mwb, on wet basis was calculated by using Eq. (1). The procedure was repeated for every one hour interval till the end of drying.

$$\mathrm{Mw} = \mathrm{Mp} \times \frac{(\mathrm{Mi} - \mathrm{Mf})}{(100 - \mathrm{Mf})}$$

$M_W = 15 \times \frac{(85.33-10.76)}{(100-10.76)}$

$M_W = 12.53$ kg

2.47 kg of moisture is to be removed from 15 kg of turmeric

Where,
M_p = Mass of product to be dried=15 kg
M_i = Initial moisture content in turmeric =85.33%
M_f = Final moisture content=10.76%
Q= $Mw \times h_{fg}$
Now, $h_{fg} = 4186(597 - 0.56 \times T_{pr})$
T_{pr}= Product temperature = 26^0C
h_{fg}=$2438.09 KJ/kg$
=$2.43 MJ/kg$
h_{fg}= Latent heat of evaporation
Q= $M_w \times h_f$
= 12.53×2.43
= $30.44 MJ$

B. *Total collector area required:*

Assuming the efficiency of collector (η) = 24%
(Generally efficiency of flat plate collector is 24-28%. But by Using Reflector Surfaces the Flat Plate Collector Efficiency can be enhanced up to 30%)
Intensity of radiation (I) = 800 W/m^2
According to Solar Radiation Hand Book data by Solar Energy Centre, MNRE Indian Metrological Department it gives the 25.12MJm^2 per day.
Assuming area of flat plate collector to be 0.7m^2
Energy retracted from FPC= η×25.12×Area = 5.72 MJ per Day
Total Energy supplied from FPC =7.455×7 = 36.92 MJ
The Flat Plate collector area required for supplying the essential heat energy is 0.7m^2

III. INSTRUMENTATION

In the fabricated forced convection solar dryer, the RTD sensors (range -10^0C to +200°C and accuracy ± 0.2°C) were fixed at the inlet and outlet of the solar air collector and at each tray in the drying cabinet to measure the dry bulb temperature at these locations. The ambient, temperatures were also measured near the solar dryer under the shade. A solar meter (resolution 0.1 W/m^2, accuracy ±10 W/m^2) used for measuring the global solar irradiance. Wind speed was measured with a hot wire anemometer (accuracy ± 0.01 m/s) and air flow rate was determined by measuring the air velocity by orifice meter at the blower outlet. For measuring the weight loss of the sample, an electronic weighing machine (capacity 10/20kg, resolution 1 gm) was used. In the drying experiments, boiled turmeric was used as the test samples in the dryer. Drying experiments were performed during the period March–May 2017. After the pretreatment, turmeric rhizomes were spread out uniformly on the trays inside the dryer. In order to compare the performance of the solar dryer the samples were also dried by traditional methods, i.e. open sun drying and shade drying. The reduction in moisture content was determined by weighing the sample at every hour.

IV. PERFORMANCE OF SOLAR DRYER

This chapter gives test methodology to analyze the performance of developed forced convection solar dryer for turmeric. Parameters needed to analyze the performance are recorded as per test methodology. Test methodology have been planned and executed in order to find the drying time with forced convection in solar dryer. The effect of mass flow rate of air on moisture content, moisture loss, drying rate, drying time and dryer efficiency has to be evaluated and accordingly test have been executed for both forced convection and for natural convection.

- Boiling of turmeric affect drying time. Boiling made cells of the rhizomes softer so that moisture can be easily removed, hence it is decided to carry out the experiment with boiling of turmeric rhizomes into water for 30 minutes.
- Experimentation has been carried out for drying the turmeric from initial moisture content 85.33% to final moisture content 10.76% for a fixed mass flow rate (for forced convection).
- Mass flow rate of air is kept 0.026 kg/sec through the dryer cabinet.
- With selected mass flow rate of air, time to time reduction in weight of turmeric sample, flat plate collector air inlet and collector air outlet temperature, dryer cabinet exit temperature, intensity of solar radiation are noted till final moisture content reduced to 10.76%.

V. RESULTS AND DISCUSSION

The results obtained from the experimentations carried out on the solar dryer by the mentioned methodology are presented in the following section. Total six numbers of days are required for drying of the turmeric considering nine sunshine hours (from 10 am to 6 pm). Various graphs are plotted for the study of variation of intensity of solar radiation with respect to drying time, variation of weight with respect to drying time.

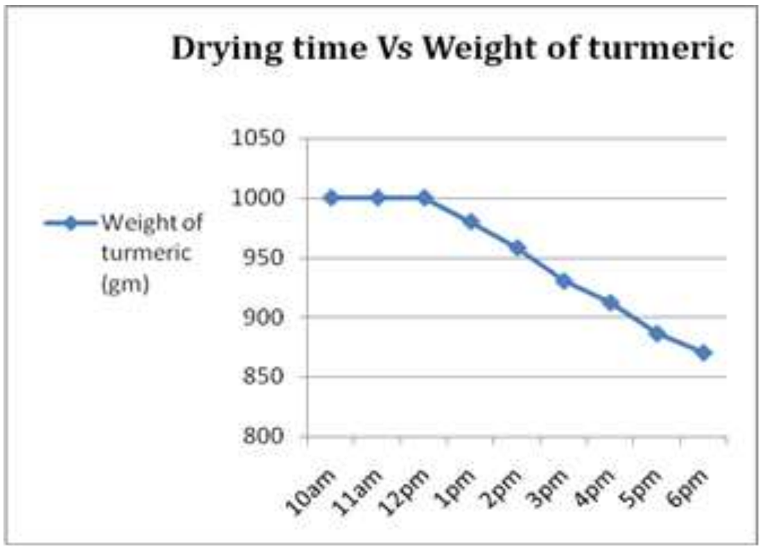
Finally both dried turmeric samples (using forced convection and natural convection) were tested in research laboratory for nutritional value and percentage of moisture present.

A. Variation of weight of turmeric with time (Forced convection):

The variation of solar intensity, weight of turmeric was measured against the drying time during the 6 days of experimentation with a constant mass flow rate.

Table – 1
Variation of weight of turmeric with drying time at a constant mass flow rate 0.026 kg/sec (for day 1)

Time (hr)	*Drying time in hr*	*Solar intensity (W/m^2)*	*Weight of turmeric(gm)*
10am	*0*	*312*	*1000*
11am	*1*	*654*	*1000*
12pm	*2*	*912*	*1000*
1pm	*3*	*1125*	*980*
2pm	*4*	*914*	*958*
3pm	*5*	*625*	*930*
4pm	*6*	*321*	*912*
5pm	*7*	*210*	*886*
6pm	*8*	*97*	*870*



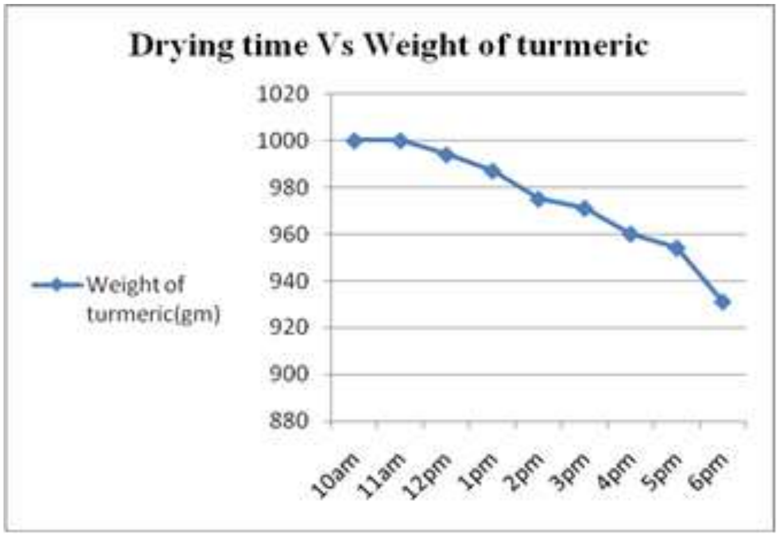
Graph 1: Variation of weight of turmeric vs. drying time for a mass flow rate of 0.026 kg/sec

B. Variation of weight of turmeric with time (Natural convection):

The variation of solar intensity, weight of turmeric was measured against the drying time during the 8 days of experimentation.

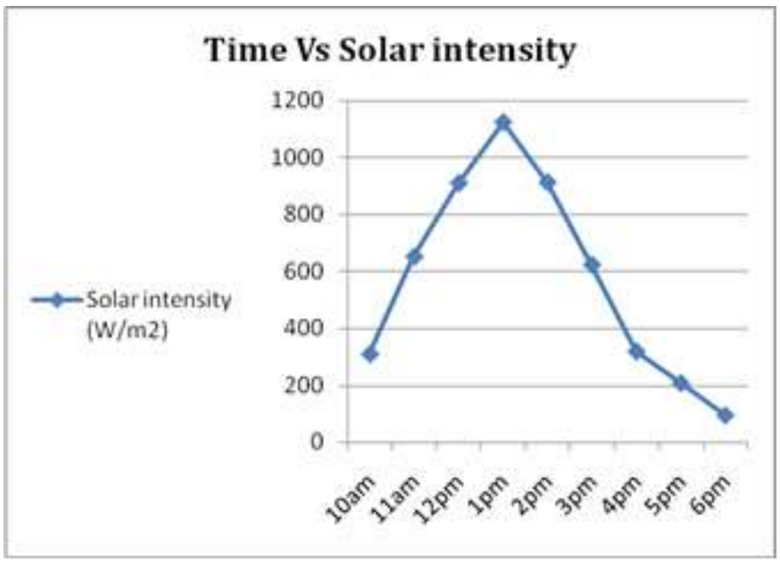
Table – 2
Variation of weight of turmeric with drying time (for day 1)

Time (hr)	*Drying time in hr*	*Solar intensity (W/m^2)*	*Weight of turmeric (gm)*
10am	*0*	*212*	*1000*
11am	*1*	*712*	*1000*
12pm	*2*	*900*	*994*
1pm	*3*	*947*	*987*
2pm	*4*	*815*	*975*
3pm	*5*	*525*	*971*
4pm	*6*	*325*	*960*
5pm	*7*	*215*	*954*
6pm	*8*	*87*	*931*



Graph 2: Variation of weight of turmeric vs. drying time for natural convection.

The experiments were conducted for six numbers of days(for forced convection) and eight number of days (for natural convection), weight of turmeric is measured hourly by using electronic weighing machine and is plotted against time also solar intensity was measured by using solar meter and plotted against time. Experiment was conducted using the mass flow rate of 0.026 kg/sec.



Graph 3: Variation of Solar intensity vs. drying time

VI. RESULT VALIDATION

To solve mathematical model and energy equation in the solar dryer, CFD software, FLUENT is used. Governing equations combined with initial boundary conditions are discretized in implicit form using the control volume method and solved using SIMPLE based approach. The solar dryer turbulence was represented by the k-ε model. Pressure based solver is used for simulation, pressure-based approach was developed for low-speed incompressible flows, while the density-based approach was mainly used for high-speed compressible flows. In pressure based solver pressure-based approach, the pressure field is extracted by solving a pressure or pressure correction equation which is obtained by manipulating continuity and momentum equations and the velocity field is obtained from the momentum equations. The solution process involves iterations wherein the entire set of governing equations is solved repeatedly until the solution converges. Steady state is considered for Air flow and heat transfer simulation. The discretization schemes were second order for all the equations, except for the pressure that used standard.

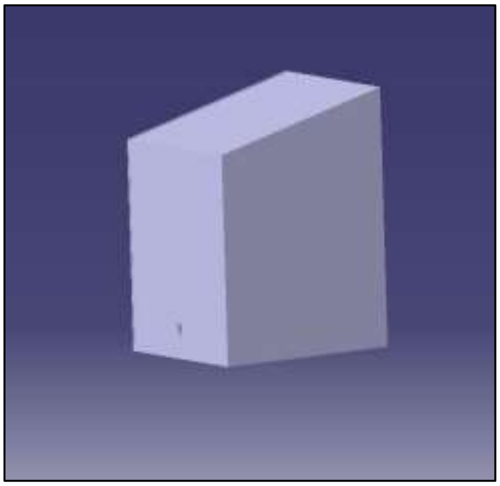


Fig. 6.1: CATIA model of Solar cabinet dryer

A. Meshing:

The meshing is most critical part of CFD simulation process. In meshing we create the grid of cells or elements at which all fluid equations will be solved. The size of grid or element will give significant impact on the computational time and hence on simulation cost. The size of element will give significant impact on solution convergence and accuracy. The 5013398 tetrahedral computational cells and 1095175 nodes are adopted for solar dryer meshing. It is found that the results almost have no variation. So, the refinement of the grids does not produce any significant differences in the results. Meshing is start on coarse mesh then quality of mesh should check as skewness. The skewness is not to exceed more than 0.98 otherwise solutions will not converge as desired or it will shows divergence error. Some models and settings required the skewness limit range 0.85 to 0.95. The overall range of skewness is 0 to 1, best is 0 and worst is 1.

Fig. 6.2: Meshing of Solar cabinet dryer

The cell shape selected is triangles for 2D and tetrahedron for 3D. The number of element directly affect on computational time and final result. If the number of element is higher, then it gives better final result but increases the computational time. Statistics of node, element for solar dryer is given in table 3

Table – 3
Statistics of nodes and elements

Item	*Setting*
Nodes	*1095175*
Elements	*5013398*

B. Boundary conditions:

The boundary condition for solar dryer simulation is considered as air inlet, outlet, and cabinet as shown in table 4 and 5. For air inlet, inlet velocity condition is taken because we use the air at velocity of 26 m/s for forced convection and 5 m/s for natural convection. Whereas temperature taken was 55.8^{0}C for forced convection and 56.5^0 C for natural convection.

Table – 4
Initial boundary conditions for Solar Dryer (Forced convection)

Modeled Equation	*Values*	*Turbulence*	*Energy*
Air Inlet	*V=26 m/s*	*K=Constant ε=Constant*	$T_{inlet}=55.8^0C$
Outlet	*Outflow*	*Extrapolate from the interior of domain*	
Wall	*No slip*	*Wall function*	*Q= Constant*

Table – 5
Initial boundary conditions for Solar Dryer (Natural convection)

Modeled Equation	*Values*	*Turbulence*	*Energy*
Air Inlet	*V=5 m/s*	*K=Constant ε=Constant*	$T_{inlet}=56.5^0C$
Outlet	*Outflow*	*Extrapolate from the interior of domain*	
Wall	*No slip*	*Wall function*	*Q= Constant*

C. Results for Forced Convection:

1) Velocity Distribution in solar dryer:

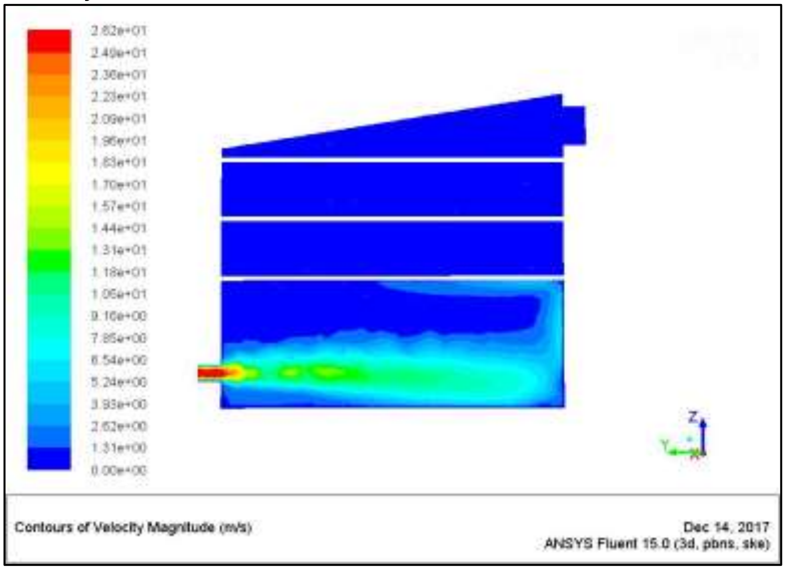


Fig. 6.3: Velocity distribution in solar dryer for forced convection

Fig. 6.3 shows the velocity distribution inside solar dryer, inlet velocity of air 26 m/s. In velocity distribution diagram eddies are developed at corner. The maximum velocity is at inlet pipe has magnitude 26 m/s and inside the dryer the velocity is 5 m/s as seen in Fig 6.3. We can say that air with uniform velocity is circulated across the trays where we are placing turmeric for drying purpose.

2) Temperature distribution in solar dryer:

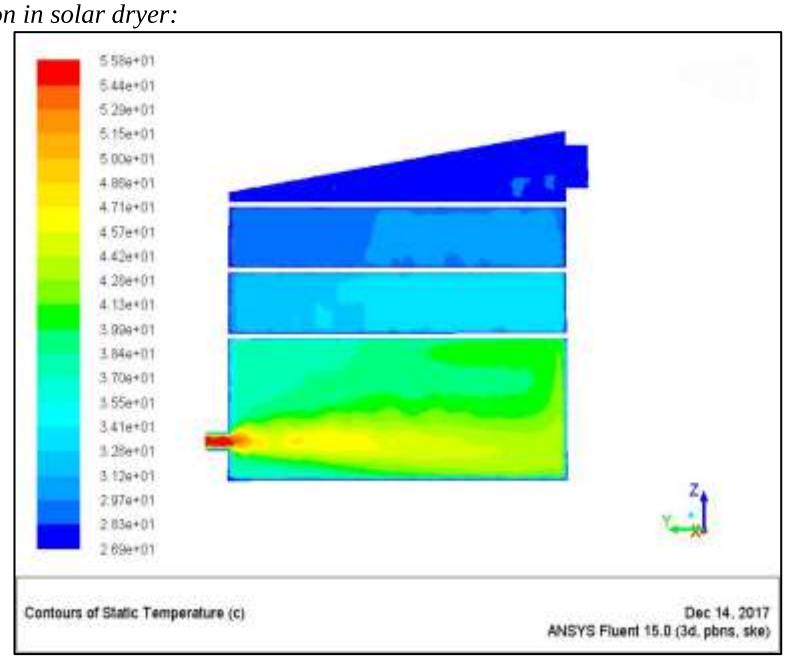


Fig. 6.4: Temperature distribution in solar dryer for forced convection

In fig. 6.4 temperature Distribution in solar dryer shows that uniformity of temperature has been achieved in solar dryer. Thermocouples were used to measure the temperature inside the dryer. Fig. 6.5 shows temperature distribution on central Z-plane with uniform temperature.

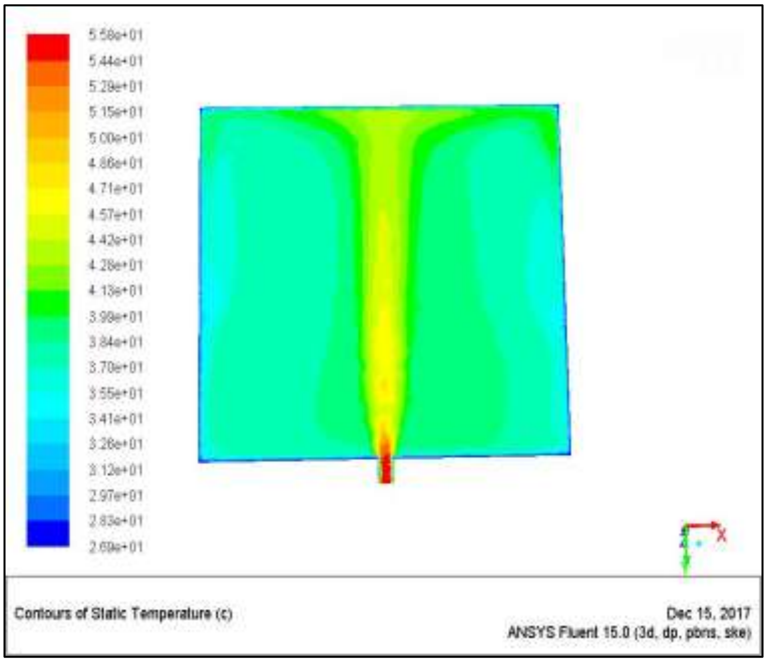


Fig. 6.5: Temperature distribution in solar dryer for forced convection across Z plane

D. Results for natural convection:

1) Velocity distribution across solar dryer:

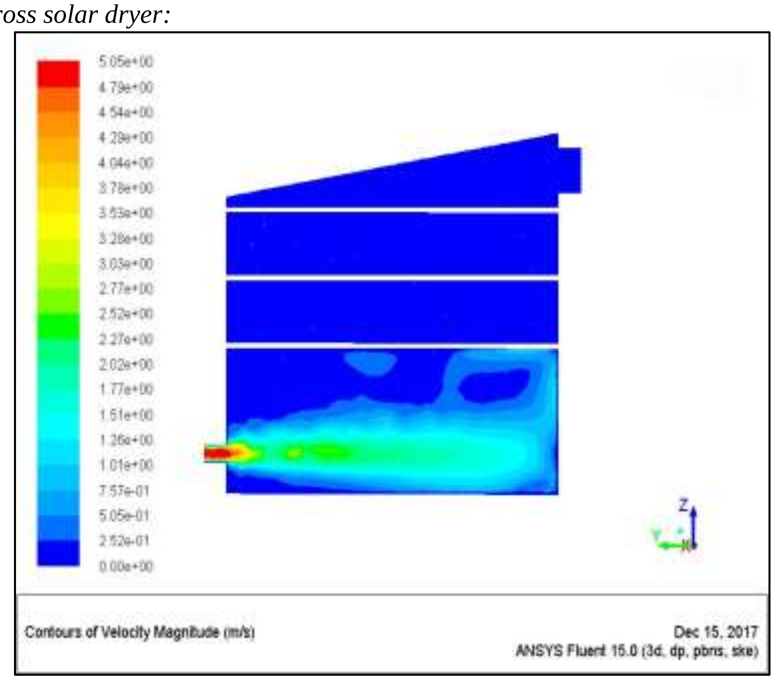


Fig. 6.6: Velocity distribution in solar dryer for natural convection

Fig. 6.6 shows the velocity distribution inside solar dryer, inlet velocity of air 5 m/s. In velocity distribution diagram eddies are developed at corner. The maximum velocity at inlet pipe has magnitude 5 m/s and inside the dryer the velocity is 2 m/s as shown in Fig. 6.6. We can say that air with uniform velocity is circulated across the trays where we are placing turmeric for drying purpose.

2) Temperature distribution across solar dryer:

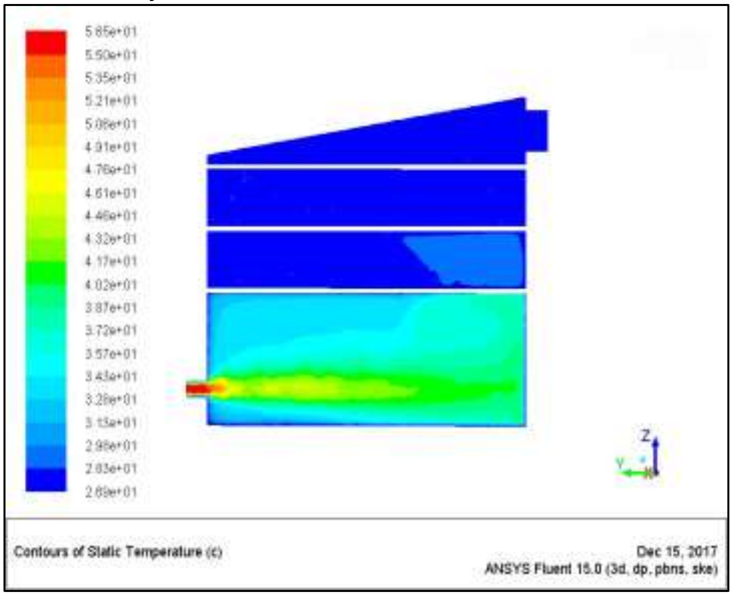


Fig. 6.7: Temperature distribution in solar dryer for natural convection

In fig. 6.7 temperature distribution in solar dryer shows that uniformity of temperature has been achieved in solar dryer. Thermocouples were used to measure the temperature inside the dryer. Fig. 6.8 shows temperature distribution on central Z-plane with uniform temperature.

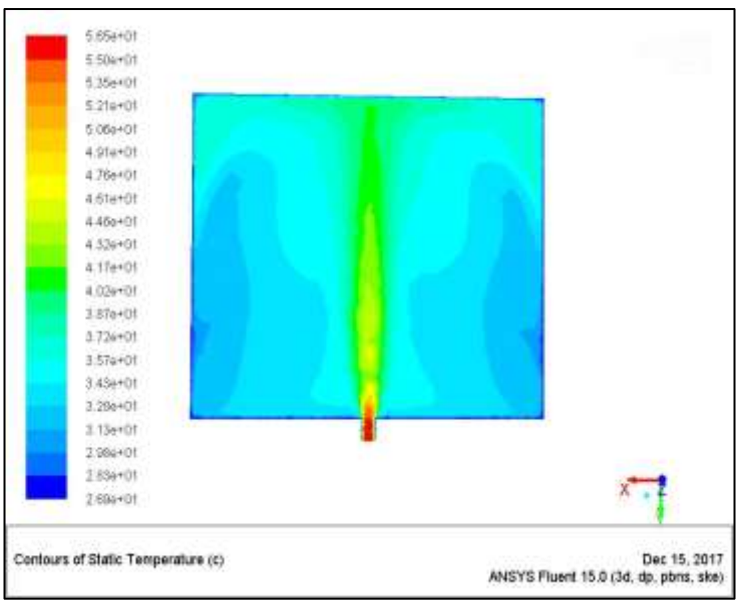


Fig. 6.8: Temperature distribution in solar dryer for natural convection across Z plane

E. Validation:

Table – 6
Comparison of experimental and simulated temperature values (Forced convection)

Temperature	*Experimental Result*	*Simulated Results*	*Deviation*
Inlet	*55.8^0 C*	*55.95^0 C*	*0.26%*
Outlet	*32^0 C*	*29.1^0 C*	*9.06%*
Cabinet	*48.3^0 C*	*44.6^0 C*	*7.66%*

Table – 7
Comparison of experimental and simulated temperature values (Natural convection)

Temperature	*Experimental Result*	*Simulated Results*	*Deviation*
Inlet	*56.5^0 C*	*56.65^0 C*	*0.28%*
Outlet	*29^0 C*	*27^0 C*	*6.8%*
Cabinet	*44.6^0 C*	*40.2^0 C*	*9.86%*

As the deviation between simulation and experimental results are below 10 % hence we can conclude that selected mathematical models very closely represent actual physical condition.

VII. Conclusion

In this project work, the forced convection solar dryer for turmeric is designed, developed and successfully tested experimentally. The boiled turmeric rhizomes have been dried with the forced convection solar dryer. The effect of drying time, air mass flow rate, solar intensity, drying time has been evaluated.
Following conclusions have been arrived from the experimental investigation carried out in the present work of solar turmeric dryer.

- The drying experiment conducted with boiled rhizomes and it is found that the complete drying cycle could be attained within 48 sunshine hours for forced convection which is very less compared with open sun drying.
- Dried turmeric production is possible with developed solar dryer in much shorter time with better quality.
- All this work put forward an extension of renewable energy based drying technology in the field of turmeric drying so that it can be economical for small scale farmers.

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