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Simulation and Experimental Investigation on Active Solar Coffee Dryer

Tefera Abera[1], A. Venkata Ramayya[2]
Hadiya Zone Water, Mines and Energy Department, P.O.Box:378, Hossana,Ethiopia,
Email: teferaabera74@yahoo.com
[2] Professor, Jimma University Institute of Technology, Jimma, 378, Ethiopia, Email: ganikavenkata@gmail.com

***Abstract* — Considering the size and relevance of coffee industry to the Ethiopian economy this work presents the design, prototype development, analytical and numerical simulation as well as experimental investigation on an active solar coffee dryer. The solar collector and dryer system configuration has been optimized for minimal pressure drop by incorporating guide vanes and minimizing flow separation tendency using numerical simulation on ANSYS. The effect of air mass flow rate on optimal depth of collector, temperature rise and pressure drop were characterized including the effect of variation in solar insolation using CFD approach. By comparing different dryer configurations based on pressure drop and air flow uniformity, a new dryer configuration prototype was developed. In addition, thermal performance of the solar air heater was evaluated experimentally at three different airflow rates on a collector with corrugated absorber plate and another collector with flat absorber plate. High collector outlet temperature and efficiency were observed in a collector with corrugated absorber plate. The effect of depth of grain, moisture content on wet basis, airflow rate and humidity of air were explored for parametric sensitivity vis-à-vis drying time. Within 5 hours, coffee bean dried from 29% moisture content to 12.3% on a clear sunny day and within 7hours from 19% moisture content to 11.1% on a partially overcast day. Average thermal efficiency of the dryer was found to be 50.5% for clear sunshine day and 36.9% for partial overcast day. A good agreement has been observed between the experimental results and the CFD temperature rise predicted output with a deviation of 7.5%. Analytically predicted drying time compared with experimentally measured drying time within a 12.9% deviation. The cost -to-benefit analysis with a comparative assessment on traditional mode of coffee drying has been done and the payback period is found to be 1.03 years with significant benefits..**

Key words: **Solar coffee drying, CFD simulation, Drying time, Active solar dryer**

I.INTRODUCTION

Coffee is the second most internationally traded product in which more than 80 countries including Ethiopia cultivate it to be exported as raw, roasted/soluble product to more than 177 countries worldwide and provide a livelihood for an estimated 100million people around the world [1]. Ethiopia, the world's 5th largest coffee producer (International Coffee Organization, 2012) is widely regarded as the home of the Arabica bean. Arabica coffee beans have a richer, fuller flavor and account for roughly 80% of the total coffee consumed worldwide. Arabica, meaning 'coffee shrub of Arabia' is indigenous to Ethiopia.

The production of coffee is of enormous relevance for Ethiopia, playing a dominant role in economy, ecology, socio-cultural and spiritual terms. The agriculture based Ethiopian economy is highly dependent on coffee since it accounts for more than 25% of the GNP and 65% foreign currency of all export earnings. Coffee production in Ethiopia is the driving force since over a million coffee farming households and about 25% of the total population of the country is dependent on production, processing, distribution & export of coffee [1, 2].

For coffee producers, the drying process of the coffee is critical for obtaining a good quality and a good price for their product. The drying process of the coffee grain is very important for preserving the quality of the coffee, because it reduces the humidity content of the grain in order to be stored and impedes the germination of the seed. In the process of drying, heat is necessary to evaporate moisture from the grain and a flow of air is needed to carry away the evaporated moisture. Depending on the wetness conditions of the grain surface, the drying rate is controlled by one of two basic mechanisms; the migration of moisture from the interior of an individual grain to the surface, and the evaporation of moisture from the surface to the surrounding air. These processes are affected by mass flow rate of air, humidity of air, grain moisture content, temperature rise within the air heater and air flow uniformity. The objective of the present analytical and numerical simulation is to design and prototype development of solar coffee dryer by minimizing pressure drop and flow separation tendency to investigate the effect of depth of grain, moisture content on wet basis, airflow rate and humidity of air on drying time followed by experimental testing for verification and validation..

II. LITERATURE REVIEW

Drying of agricultural products dates back to the beginning of civilization. The use of solar energy and air movement provided the major method of moisture removal in the field. Crops for human consumption were occasionally dried in ovens or by hanging in heated rooms. Commercial dryers were primarily used for dehydration of fruits, vegetables, and hay, drying of seed corn with heated air, and drying hay in the barn, usually with unheated forced air. Commercial and large scale farm drying became a common practice after World War II. The increase in drying practice was coupled to the rapid increase in mechanization and increase in land labor productivity. Large quantities of moist or wet products were produced at harvest requiring moisture removal to avoid loss during subsequent handling and storing. Speed of operations from harvest to storage forced the consideration, study, and use of heated air for drying. Many studies have been reported on solar drying of agricultural products in the tropics and subtropics. However, systematic researches on solar coffee drying have not been reported in the open literature and this study is an attempt in this regard considering its significance in Ethiopian context. Basically, there are three types of solar dryers; solar natural dryers, solar active dryers and solar hybrid dryers. Either natural or active solar dryer can be direct solar dryers, indirect solar dryers, and mixed-mode dryers. Focusing up on the objectives of this study, the literature review is summarized in Table1.

III. MATERIALS AND METHODS

In this section the work is subdivided in to data collection, research design, and CFD simulation and, prototype development and experimental work (see Fig1).

A. Research design

Research design would introduce the conceptual solar dryer design specifically meant for drying coffee bean but other agricultural products can also be dried using this solar dryer. Desired research design issues are drying time, pressure drop within the system, dryer design, etc.

Dryer design was formulated as a function of the initial moisture content of coffee bean, initial mass of coffee bean, average ambient temperature, etc. The desired moisture level of the dried coffee bean was taken to be 11.5% (w.b.). Relevant climatic data were taken from Jimma branch meteorology office. The conditions/assumptions for design of the dryer are provided in Table2. Pressure drops occur at entrances, transitions, exits and elbows due to energy dissipation by eddies and by distortion of velocity profiles. However, the major pressure loss in a dryer is caused by the coffee bed, treated as packed bed. The pressure drop through packed beds is the result of frictional losses and inertia characterized by the linear dependence of flow velocity and quadratic dependence of flow velocity respectively as can be seen from the well-known Ergun's Equation [11]

$$\Delta p=\frac{150\mu v_s Y(1-\varepsilon)^2}{D_p^2\varepsilon^3}+\frac{1.75 Y\rho_a v_s^2(1-\varepsilon)}{D_p\varepsilon^3} \quad (1)$$

TABLE 1 SUMMARY OF LITERATURE REVIEW

Authors	Tasks performed	Methodology used	Results obtained	Validation
Jain [3]	modeled the system performance of multi-tray crop drying using an inclined multi-pass solar air heater with in-built thermal storage	mathematical modeling	Crop moisture content decreases with the drying time of the day, the thermal efficiency of drying increases with increase in mass of the crop and Different drying rate with in different drying trays due to the variation in crop temperature.	Analytical
Yaldiz [4]	mathematical modeling of thin layer solar drying of sultana grapes	Mathematical modeling	Drying behavior of Sultana grapes with drying air temperature range of 32.4 to 40.3°C and velocity of 0.5 to 1.5m/s.	Experimental
Othieno [5]	designed a portable direct type natural convection solar dryer	Experimental testing	Due to low airflow was not successful	
Pangavhane [6]	developed and tested a multipurpose natural convection solar dryer	Experimental testing	The moisture content reduced from 49.59 (%db) to 17) within 15days in shade drying and 7 days in open sun drying, while solar dryer dehydrates the grapes within 4 days.	qualitative analysis
Sarsavadia [7]	designed and introduced an active solar-assisted dryer for dehydrating onions	Experimental testing	The energy required per unit mass of water removed was found between 12.040 and 38.777 MJ/kg water.	Experimental
Janjai [8]	evaluated the performance of a roof-integrated solar dryer for herbs and spices and compared results with traditional drying m	Experimental testing	By solar dryer higher quality of dried spices and higher added-value and rapid capital return has been proved.	Experimental
Aklilu [9]	experimental analysis for performance evaluation of solar dryer on potato slices	Experimental testing	the drying time compared to sun drying reduced by about 19%	Experimental
Habtamu [10]	performed simulation of solar cereal dryer using TRNSYS	TRNSYS Simulation model	Temperatures rise of 14-28°C (from 8:30AM- 4:00 PM) higher than the ambient air temperature in a clear day	Analytical with TRNSYS simulation

When the air flows through the solar dryer system, due to friction, sudden construction and sudden expansion, the air pressure drops along the length of the flow pipes and channel. Pressure drops along the length of the flow pipes is given by equation (2) below

$$\Delta p = f\frac{L}{D}\frac{(\rho V^2)}{2} \qquad (2)$$

Pressure drops along the length of the flow channel is given by equation (3) below

$$\Delta p = f\frac{L}{D_h}\frac{(\rho V^2)}{2} \qquad (3)$$

Frictional losses are mainly due to flow separation whether it be separation from a sudden expansion or diffusers, vena contracta in a sudden contractions or high angled nozzles, or separation/secondary flows in a pipe bend. Pressure drops by minor losses is given by equation (4) below

$$\Delta P = \rho K_L \frac{V^2}{2} \qquad (4)$$

The amount of water to be removed from coffee bean is calculated by using equation (5).

$$m_w = \frac{(MC_{wi} - MC_{wf})m_i}{100 - MC_{wf}} \qquad (5)$$

Estimation of drying time can be calculated by using equation (6)

$$t_d = \frac{M_w}{m_a*(\omega_f - \omega_i)} \qquad (6)$$

The equilibrium moisture content, MC_e, is the moisture content of a product that is in equilibrium with air at a particular mean dry-bulb temperature and relative humidity that would be attained by the grain over in finite time, at a constant value of air relative humidity and temperature. Equilibrium moisture content equation for coffee as given by Guggenheim-Anderson-de Boer (GAB) model [12]

$$MC_e = \frac{a.b.c.\phi}{[(1-b.\phi).(1-b.\phi+b.c.\phi)]} \qquad (7)$$

Dryer thermal efficiency can be calculated as [13]

$$\eta_{therm} = \frac{m_w h_{fg}}{m_a Ca(T_0 - T_i) + m_a Ca(T_{iht} - T_a) + E_b} \qquad (8)$$

B.CFD simulation

Computer simulations are a nice inexpensive way to verify the effectiveness of a design before prototyping it. During the design process of the solar dryer, several computational fluid dynamic (CFD) simulations will be performed to validate design decisions. The simulations were performed using ANSYS FLUENT12.1, commonly used and commercially available CFD software. Using these simulations optimal uniform temperatures and air flow (the two most important parameters for dryer) were determined. Considering merits and demerits of different configurations and to minimize the pressure drop throughout the system by using ANSYS12.1, different dryer configuration based on pressure drop and uniform air flow distribution have been compared.

C. Experimental work

The solar dryer discussed here, consists of a solar air collector, a drying Chamber, blower and appliances. An outlay of the dryer fabricated is given Fig.2 .The solar collector with dimension of 2m*1m*0.15m having 0.15m channel depth has 29 mm thick on the bottom chipwood and plywood insulation. In the present study, its longitudinal axis is oriented along the N–S direction. The collector is inclined at an angle of 18^0 with the horizontal. The absorber plate consists of 1mm thick aluminum sheet metal blackened on the sun facing side. The cover material of the collector is 5mm thick commercial glass. The lower end face of the collector (1 m x 0.15 m) is connected with diffuser which is connected with blower by 4"pipe whereas its higher face end is connected to the rectangular duct of the chamber

TABLE 2 DRYER DESIGN CONDITIONS

Items	Conditions
Location	Jimma
Crop type	Coffee bean
Initial coffee mass or wet coffee mass to be dried	10kg-100kg
Initial percentage moisture content of coffee on wet basis	50%-70% w.b
Final percentage moisture content of coffee on wet basis	11.5% w.b
Ten years minimum and maximum average ambient air temperature	20-27.9^{0}C
Ten years minimum and maximum average ambient relative humidity	56-83%
Maximum allowable temperature for drying coffee beans	60^{0}C
Wind speed	2.5m/s
Vertical distance between two adjacent trays	10cm

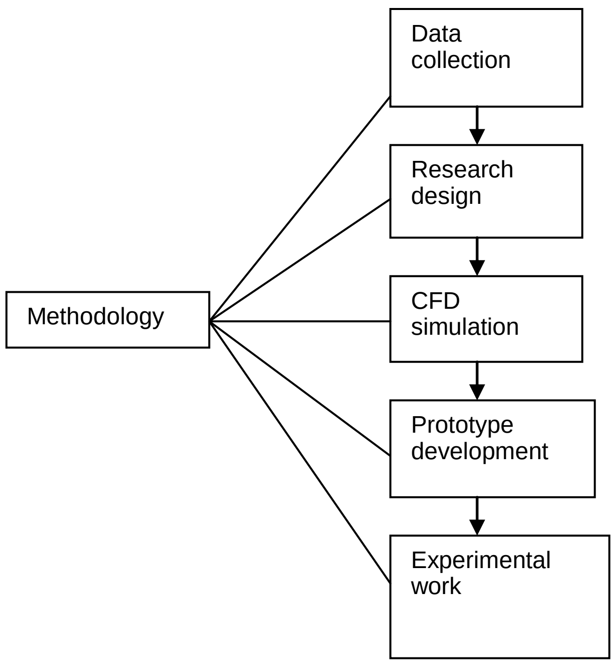

Fig. 1 Pictorial view of experimental setup

IV. Results And Discussions

A. Analytical results

The analytically computed values of the moisture to be removed, drying time, equilibrium moisture content and pressure drop are given in Figs. 3–6. Figure3 illustrates the variation of the moisture to be removed with initial coffee mass at fixed initial moisture content 55% in wet basis. It is shown that moisture to be removed is directly proportional to initial coffee mass at fixed initial moisture content which means moisture to be removed increases with increasing initial coffee mass and vice versa. Figure 4 presents drying time variation with mass flow rate of air at fixed coffee mass (20kg) and dryer inlet temperature (38^{o} C). It is seen that the drying time is a function of mass flow rate of air and decreases with mass flow rate of air at fixed inlet condition. Figure 5 depicts the variation of the equilibrium moisture content with the relative humidity of the ambient air. It is observed that the equilibrium moisture content is a function of relative humidity. Equilibrium moisture content increases with increasing relative humidity. Figure 6 presents the variation of the pressure drop with the mass flow rate for collector flow channel of 0.05 m, 0.1m and 0.15 m. It can be inferred that the pressure drop is depending on of mass flow rate and the collector channel depth. Pressure drop increases with increasing mass flow rate, but decreases with increasing collector channel depth.

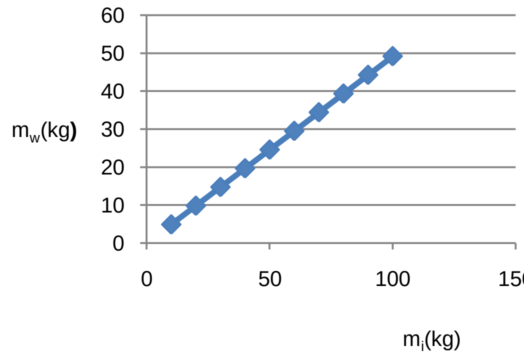

Fig. 2 The variation of moisture to be removed vs initial coffee mass at fixed initial moisture content (MC_{wi}=55%)

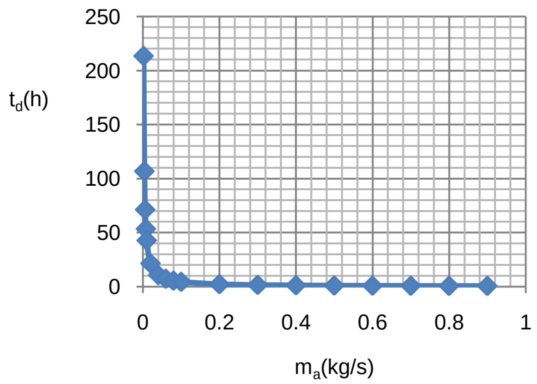

Fig. **3** Drying time variation with mass flow rate of air at fixed coffee mass (20kg) and dryer inlet temperature (38^{o})

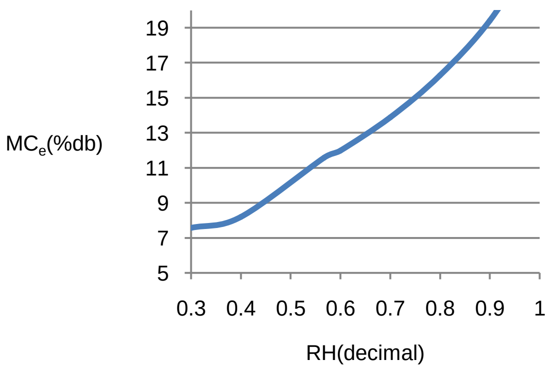

Fig. 4 Variation of equilibrium moisture content with relative humidity of drying air at fixed temperature

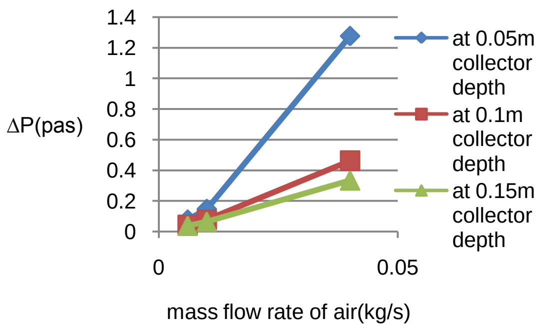

Fig. 5 System Pressure drop variation with collector depth at different mass flow rate of air

B.CFD simulation results

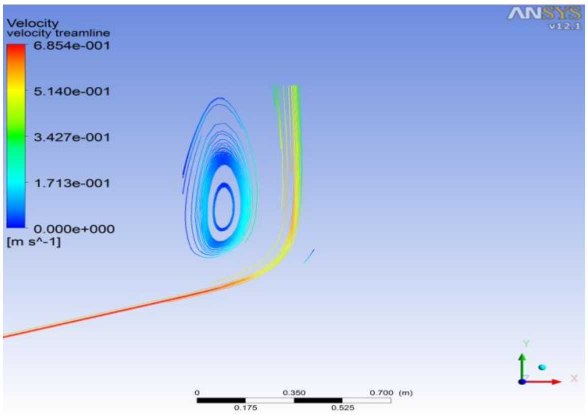

Fig. 6 Velocity streamline for sharp edge connected configuration

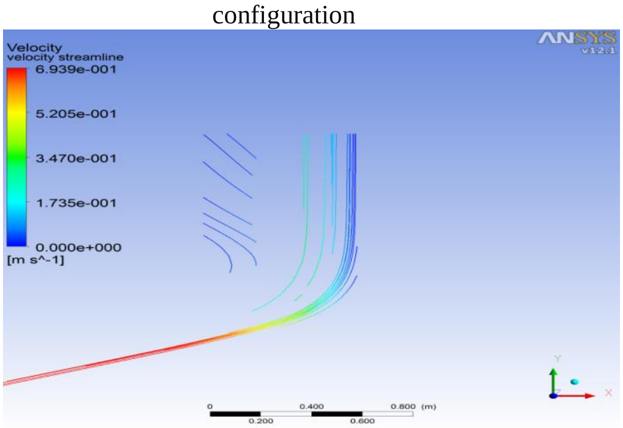

Fig.7 Velocity streamline for smooth edge connected dryer Configuration

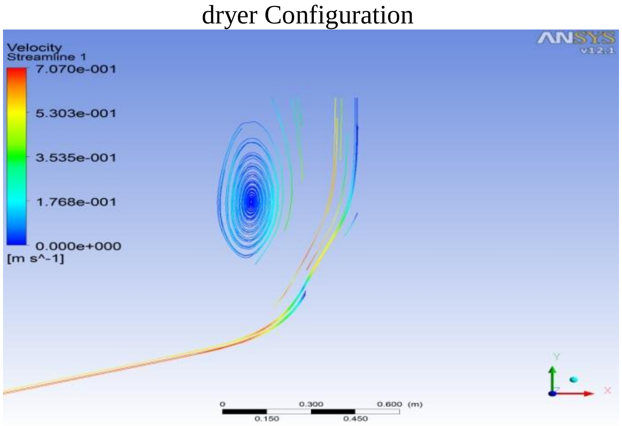

Fig. 8 Velocity streamline for smooth curve then diffuser connected d

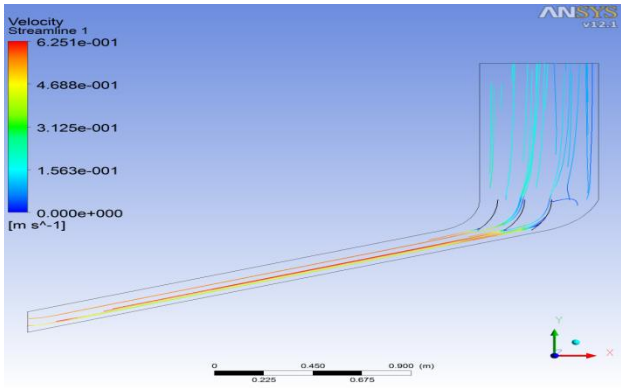

Fig. 9 Velocity streamline for smooth curve connection with guide vanes

TABLE 3 MESH SENSITIVITY STUDY

Types of mesh	**No. of nodes**	**No. of elements**	**Pressure drop(Pascal)**	**% change**
Coarse	580	324	0.1429	4.67
Medium	1834	1236	0.1449	3.34
Fine	6094	4580	0.1496	0.2
Fine	8832	6720	0.1499	0

The tests proved that grid type did influence the obtained results, but the percentage change was very small throughout the mesh size (8832) finally used.

Comparing Fig.7-Fig.10 based on eddy or secondary flow formation qualitatively, smooth curve connection with guide vanes configuration has very small eddy or secondary flow formation as compared to other remaining three configuration types. Therefore, smooth curve connection with guide vanes is best among others.

Comparing Fig.7-Fig.10 based on pressure drop in quantitative terms, smooth curve connection with guide vanes configuration has very small pressure drop than any other three dryer configurations as shown in Fig.11. By comparing velocity streamlines for four dryer configurations qualitatively, velocity streamline for smooth curve connection with guide vanes (Fig.10) is better than any other dryer configuration type. Velocity streamlines shows for both smooth edge connected dryer configuration and for smooth curve then diffuser connected dryer configuration have high recirculation flow in the one side of dryer cross-section. This recirculation flow results in non uniform drying rate for grain. For smooth edge connected dryer configuration (Fig.8), recirculation flow is small as compared to Fig.7 and Fig.9 but as compared to Fig.10, still there is flow disturbance. Finally, comparing four dryer configuration based on pressure drop and air flow uniformity smooth curve connection with guide vanes better than any other three configuration type (smooth curve then diffuser connected dryer configuration, smooth edge connected dryer configuration and sharp edge connected configuration).

Smooth curve connection with guide vanes configuration was used for dryer prototype development and fabrication. The variation in temperature rise with the flow channel depth is displayed in Fig.12, which indicates that the temperature rise can be increased with increasing flow channel of collector.

C. Experimental results

Thermal performance of the solar air heater was evaluated experimentally at three different airflow rates on two different types of flat plate collector. The maximum outlet air temperature of 57^{o}C and 43^{o}C was obtained from the smooth flat plate collector for the lowest (0.0416 kg/s) and highest (0.0905 kg/s) airflow rates, respectively. The maximum outlet air temperature of 58^{o}C and 48^{o}C was obtained from the corrugated flat plate collector for the lowest (0.0416 kg/s) and highest (0.0905 kg/s) airflow rates, respectively (see Fig.13). Variation of drying tray inlet temperature and tray outlet temperature with drying time is illustrated in Fig.14. The variation at the beginning of experimentation was 17^{o}C for clear sunshine day. The variation decreases gradually and at the end of drying period was 1^{o}C for clear sunshine day. The time required to dry coffee from an initial moisture ratio of around 1 to the final moisture ratio of around 0.15 was 5 hours for clear sunshine day (Fig.15).

D. Validation

Validation and verification focus on the comparison between the predicted output and the experimental results for solar plate collector as well as drying time. A CFD simulation on solar collector absorber plate has been carried out run in this regard using the same absorber configuration and average parameters employed in experimental work. A great agreement has been observed between the experimental results and the CFD temperature rise predicted output with a deviation 7.5 %(Fig.18). Between analytically predicted drying time and experimental drying time there was 12.9% deviation (Fig.17).

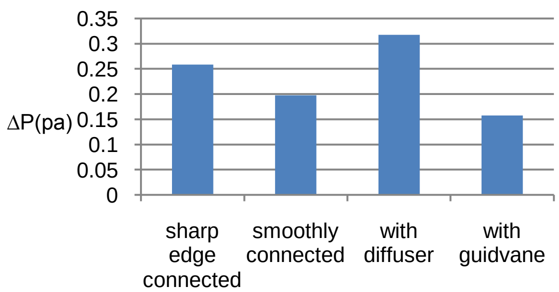

Fig.10 Comparison different geometry for pressure drop

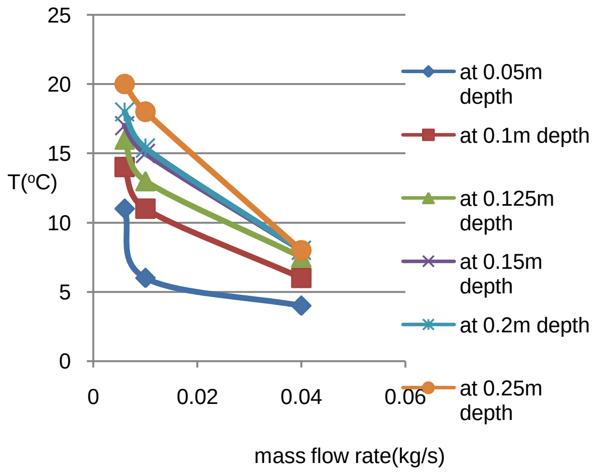

Fig. 11 Temperature rise of air at different collector depths

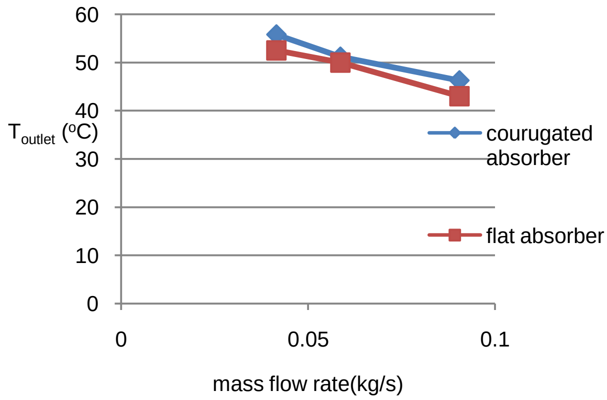

Fig. 12 Variation of outlet temperature with mass flow rate

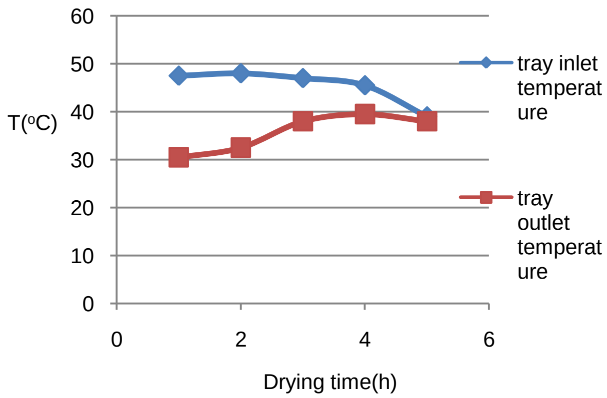

Fig. 13 Variation of drying tray inlet and outlet temperatures during drying time for clear sunshine day

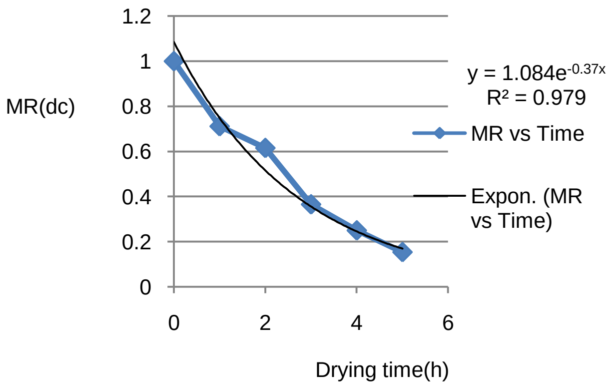

Fig. 14 Variation of moisture ratio against drying time for clear sunshine day and the curve fit

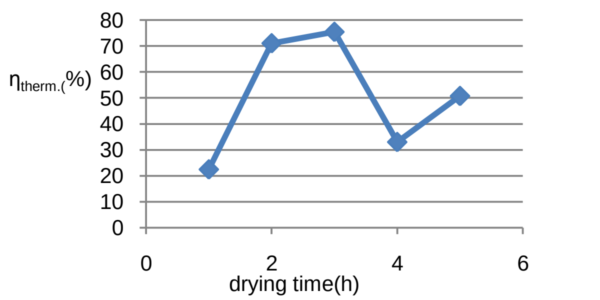

Fig.15 Variation of thermal efficiency of dryer during drying time for clear sunshine day during experimental; testing

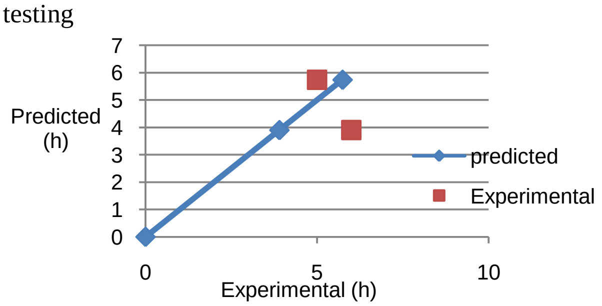

Fig.16 Comparison of drying time between predicted with experimental

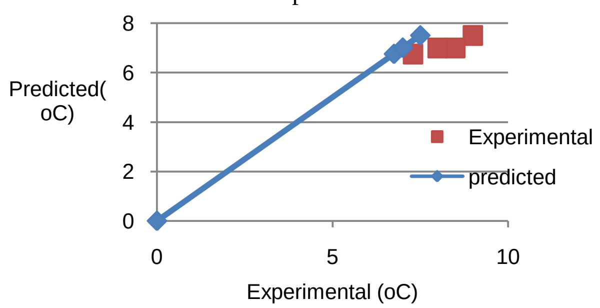

Fig.17 Comparison of temperature rise in solar collector between predicted with experimental

TABLE 4 EXPERIMENTAL VALIDATION OF COLLECTOR

One cover flat absorber at 22 l/m²s		**Experimental result reported [14]**		**% deviation**
$\frac{T_i - T_a}{I_t}$(m²°C/w)	ηi(%)	$\frac{T_i - T_a}{I_t}$ (m²°C/w)	ηi(%)	11.5
0.015	35.1	0.015	39.7	

The obtained efficiency result was lower than that was reported [14] but within acceptable range as shown in above Table 4.

E. Cost analysis

The detailed cost analysis carried out was reported in [15], but the summary of cost analysis is presented here in Tables 5-6 along with fairness criteria used for comparison

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TABLE 5 SOLAR DRYER COMPARISON WITH TRAY DRYING

Drying system	**Production capacity**	**Drying time**	**Capacity of coffee dried per month**
Tray drying	200kg in (1m*25m ground area)	15days	400kg
Solar dryer	100kg in (1m*4m ground area)	3days	1000kg

By using tray drying one can produce a maximum 2800kg of coffee bean within seven working months in 25m² ground occupied area. By using 6 solar dryers (occupying the same area) r one can produce a maximum 42000kg of coffee bean within seven working months i.e. one can dry 39200kg more coffee bean.

Using the standard cost estimation models and the present day market costs for the drying system components involved, the cost saving associated with solar coffee dryer is determined to be 11,553 Birr per annum resulting in a payback period of 1.03 year, a highly attractive proposition in deed. The details are presented in Table 6.

TABLE 6 SUMMARY OF SOLAR DRYER COST ANALYSIS

Coffee drying per year	42000kg
Capital investment	11,890ETB
Annual Cost saving	11,553ETB
Payback period	1.03year

V. CONCLUSIONS AND RECOMMENDATIONS

A. Conclusion

A CFD simulation to predict the effect of different parameters on solar collector-dryer system thermal performance and pressure drop for flat plate collector has been conducted. It is found that increasing the mass flow rate through the air heaters results in higher efficiency but the pressure drop is also increased at fixed channel depth. Increasing the channel flow depth results in increasing the system efficiency and collector outlet temperature, while pressure drop decreased for fixed mass flow rate of air. Based on the CFD simulation driven optimization results, a small scale prototype forced convection solar dryer was designed and constructed for drying coffee bean based on the optimized configuration and used for experimental investigation..

Thermal performance of the solar air heater was evaluated experimentally at three different airflow rates on two different types of flat plate collector configurations. The maximum outlet air temperature of 57^oC and 43^oC was obtained from the smooth absorber plate collector for the lowest (0.0416 kg/s) and highest (0.0905 kg/s) airflow rates, respectively. The maximum outlet air temperature of 58^oC and 48^oC was obtained from the corrugated absorber plate collector for the lowest (0.0416 kg/s) and highest (0.0905 kg/s) airflow rates, respectively. Efficiency and outlet temperature for corrugated absorber plate was higher than the flat absorber plate

The thermal efficiency as well as drying time of solar drying system is affected by the properties of coffee beans like moisture content as well as ambient conditions, which include solar irradiance, ambient temperature, ambient relative humidity and mass flow rate of air. In this regard analytical simulation of the drying process has been carried out and useful insight provided

The moisture content of the coffee was reduced from 29% to 12.3% after 5h for clear sunshine day and average thermal efficiency of the dryer was determined to be 50.5% for clear sunshine day.

When predicted output was compared with the experimental results, a good agreement has been observed between the experimental results, the CFD and analytically predicted output.

B. Recommendations

Although the findings of present study have shown that a considerable improvement can be achieved in dryer configuration, pressure drop and temperature rise within collector by incorporating guide vanes and minimizing flow separation tendency, using numerical simulation on ANSYS, further studies both experimental and numerical are needed to improve the model and to test its performance in the field. It is in light of this that the following are recommended:

- Further studies in the whole system optimization by using CFD including pressure drop, heat transfer and mass transfer without separating collector and dryer.
- Further improvement to the system model to account for deeper coffee beds and bed shrinkage by using CFD.

Nomenclature

D	Pipe diameter
D_p	The equivalent diameter of the particle (m)
D_h	Hydraulic diameter (m)
f	Friction factor
I_t	Total solar radiation on surface (W/m^2)
K_L	Loss coefficient
L	Pipe or flow channel length (m)
m_a	Mass flow rate of air (Kg/s)
MC_e	Equilibrium moisture content (%decimal dry basis)
m_i	Initial coffee mass or wet coffee mass (Kg)
MR	Moisture ratio
m_w	Mass of moisture to be removed (kg)
ΔP	pressure drop (Pascal)
RH	Relative Humidity (decimal)
T_a	Ambient air temperature (^oC)
t_d	Drying time (h)
T_i	The collector inlet temperature of drying air (^oC)
T_{outlet}	Collector outlet temperature (^oC)
w.b	Wet basis
V	Speed of the air (m/s)
ν_s	Superficial velocity (m/s)
Y	Depth of the coffee bed (m)
η_i	Normalized collector efficiency (%)
$\eta_{therm.}$	Thermal efficiency (%)
μ	Dynamic viscosity, kg/ms
ε	Porosity
ρ_a	Density of air

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Appendix: Instruments used during experimental investigation

Parameter	**Instrument used**
Coffee Bean moisture	Proti meter
Coffee Bean Mass	Digital Precision Balance
Air Flow Rate	Anemometer
Relative Humidity of air	Digital Hygrometer
Solar insolation	Customized Black body set up
Air Temperature	Digital thermometer/ Glass Thermometer
Sky temperature	Infra red thermometer
Direction setting for Solar dryer	Compass (South facing)
Pressure drop	Manometer

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