

# Effect of Air Inlet Opening on Air Flow Rate and Drag Force of an Active Indirect Mode Solar Dryer

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**Abstract**— *The effect of air inlet opening on air flow rate and drag force of an active indirect mode solar dryers was examined. This was done in line with studies which suggested the air flow rate and drag force is affected by the air inlet area of the dryer. The air flow rate of the dryer was obtained as product of the air inlet area and velocity. The shaped of the inlet chosen were: square, rectangular, circular and triangular. The air inlet area was calculated based on the dimension and shape of the inlet. The experimental design adopted (Central Composite Rotatable Design of Response Surface Methodology gave a total of 52 runs for each experiment. The volumetric air flow rate of the dryer increased with increase in air inlet area. The values obtained ranged from 0.0006 to 0.0256 N. The air inlet area of an active indirect mode solar dryer should be increased based on the size of the dryer, to ensure efficient flow of air into the dryer, to fast track drying. The drag force increased with increase in air inlet area. The values obtained ranged from 0.0007 to 0.502 N, as the air inlet area increased across the various shape orientations. The air inlet area of an active indirect mode solar dryer should be increased based on size of the dryer, to enable the blower sufficiently drags air and circulate within the dryer for faster drying of the product.*

**Keywords**— *air inlet area, air flow rate, blower, drag force, indirect solar dryer.*

## I. INTRODUCTION

About 60% of what is harvested locally in Nigeria is lost annually, as a result of poor post-harvest operations (FAO, 2014). Drying as an essential part of post-harvest materials handling, has an important role to play in the safety and durability of agricultural materials. Most rural communities in Nigeria, generally adopt drying, as a means of food preservation, this is largely due to the fact that it adds value of the final product. Drying has been widely regarded as a convenient means of preserving agricultural materials, even beyond the limit which they are expected to be viable. Energy derived from the sun can be utilized for many purposes, ranging from heating, drying, pumping of water and cooking to production of electricity by solar cells. Solar dryers have widely been used in drying of crops, but a major challenge associated with improving its efficiency is that in designing most solar systems, prior attention is not paid to the design of air inlet and outlet vents, which invariably impairs the flow of heated air within the drying chamber. This however results in rewetting of the product

particularly at night. Studies have showed that the air inlet vent of a solar system is largely responsible for flow of air into the system and variation in temperature, which directly has bearing on the amount of free water molecules removed from the cell and surface of product at the initial stage of drying (Alamu *et al.*, 2002; Oguntola *et al.*, 2010). There is need for development of solar drying systems that will analyse and recommend appropriate air inlet spacing and size of the product, to achieve more efficient drying of crops. Such innovation will stimulate interest towards adopting active indirect mode solar drying systems for agricultural products. A survey on most solar active solar dryers constructed for drying of several crops have not taken consideration of the appropriate air inlet size that will guarantee efficient drying of crops at a reduced time. This is a major concern, as dryers that are supposed to be fitted with smaller air inlet size opening, eventually end up being fixed with bigger air inlet and vice versa, since there is no recommended air inlet area for an active indirect mode dryer of any size. Air inlet vent is one of the key

components in constructing a solar drying system. The design of a solar system air inlet vent is dependent on the solar system to be constructed and the type of product to be dried. As reported by Abdulahi *et al.* (2013), increasing the vent area by opening vent, decreases the temperature and increase the air flow within the system. They also held that adequate flow of air into the system is necessary at the early stages of drying, to eliminate free water hovering round the cell of a product as well as the surface. Alamu *et al.* (2002) designed and constructed a domestic passive solar food dryer, and suggested for hot climate passive solar dryers, a gap of 5 cm should be created as inlet air vent. Raju *et al.* (2013) in designing and fabricating an efficient solar drying system, used 7cm as air vent gap and width of 5.6cm, which was slightly higher than what was recommended by the former. Akoy *et al.* (2010) used 70cm as length and 4cm as width of air inlet opening in their design and construction of solar dryer for mango slices. A solar grain dryer with backup heater was designed and evaluated by Tonui *et al.* (2014). They used air inlet spacing of 0.5m with an air flow rate of 227m<sup>3</sup>/h, to obtain a thermal efficiency of about 58% with average drying rate of 0.0077 kg/h. Bulent-Koc *et al.* (2007) used 20cm as diameter of air inlet and outlet vents respectively in analyzing the effect of air velocity and product size when drying red pepper with solar systems. Papade and Boda (2014) in developing an indirect type solar dryer with energy storing material used an air gap of 49 cm<sup>2</sup> as inlet vent in their design. Ozumba *et al.* (2013) used 60 cm<sup>2</sup> as area for air inlet vent when they fabricated a direct absorption solar dryer. Eltawi *et al.* (2012) used 80 cm<sup>2</sup> as air inlet vent area when they designed a solar wind ventilator to enhance the cabinet dryer performance for medicinal herbs and horticultural products. An adjustable and collapsible solar food dryer was constructed (Abdulahi *et al.*, 2013). An air inlet and outlet vent area of 60 cm<sup>2</sup> as used, in contrast to 25 cm<sup>2</sup> recommended and used by Oguntola *et al.* (2010). This according to the study, allowed room for more air flow into the dryer and decreased the temperature and enhancement of removal of free water molecules, which is important at the initial stage of drying. According to Greenheck (2005), blowers are evaluated and selected at variable motor speeds. For direct drive blowers, the speed can be adjusted to meet exact performance requirement by furnishing a speed control medium. Selection charts for various blowers vary depending on the model and what it is to be used for. Manufacturers usually provide information on characteristics performance curves and charts. The required fans must be able to deliver a

suitable static pressure, in order to force the cooling air through the system. A blower is basically selected to provide the required air flow performance within its optimum operating range (Greenheck, 2005). It should also be noted that if a system desires the services of more than one fan, factors such as noise level, spacing, economy and ambient conditions may also be considered in making a final decision on the choice of a blower is made. The most critical aspect of the process of selecting a blower is the ability of the user to read the performance chart which is usually embedded on a catalogue. Typical characteristics of a fan include: break horse power (BHP), Sone and Revolutions per Minute (rpm). Blowers can be classified into the following: axial or propeller fans, centrifugal or radial fans, mixed flow fans and cross flow fans. The classification is basically determined by the nature of which air flows through the medium. In axial flow fans, the air flow is parallel to the shaft and suited for relatively larger volumes to pressure. The different types of axial fans include: propeller fans, vane fans and tube axial fans. Axial fans guarantee high air flow with relatively high pressure build up (Greentech, 2011). Centrifugal fans are type of fans which air flow is in radial direction relative to the shaft. They could be forward curve, backward curve of tabular. Centrifugal fans guarantee high pressure build up at limited flow rate. Tangential fans are useful when high flow rate and low pressure is required. They are basically applicable to large-surface air flow in devices. The air flow through the roller shaped impellers in a dual direction, from the intake area to the outflow area. Bagheri *et al.* (2012) developed an active solar dryer with varying fan speed. The system was simulated and controlled based on changing system variables accordingly to maintain optimum efficiency. In their study, the dryer efficiency was determined by considering the mathematical relationships and monitoring of the air temperature at three positions namely: The inlet and outlet of the collector as well as the outlet vent of the drying chamber. Temple and Van Boxtel (2011) investigated a control system on a laboratory tea fluid-bed dryer. A simulation model was used to combine various factors and system configuration. The model analysed the operating region of the dryer, various disturbances affecting the drying time and couple of other factors. Results obtained showed that the controlled system was significantly better than the manual system which has been in existence for decades. This same feature was adopted by Soheli *et al.* (2006). Bagheri *et al.* (2012) used an axial tube fan of 12 cm in diameter, 200 m<sup>3</sup>/h flow, 2300

rpm, 38 W, 220 V, 50 Hz alternating current (a.c.) fan to develop an active solar drying system. To effectively optimize the model, the simulated and the real fan speed were compared. It was observed that there was no significant difference between the real and simulated fan speed at probability level of 5 %. A fan with speed of 1700 rpm was used for simulation of the model, though the experiment utilized fan speed ranging from 0-2300 rpm.

## II. MATERIALS AND METHODS

The dryer was made up of the solar collector section, the drying chamber and the inlet and outlet vents, solar panels, dry cell battery and blowers. The inlet vent was of various shapes and sizes, while the outlet vent of the dryers was of the same size. The dryer had sawdust as its insulation material at the base and beneath the collector and the drying chamber of known thickness. Glass of 3mm thickness was used as transparent cover material. Plywood was used as construction material. The dryer was inclined at an angle due south and optimum slope angle of 8° from the horizontal plane of the area of study. Each cabinet was fitted with a single layer of crop tray. A blower was attached to the drying chamber to increase air flow rate of hot air within the drying chamber. Nails and screws ranging from tack nails to 5cm long were used as fasteners, to hold various component of the dryer together. Black oil paint was used to paint the dryer. All construction work was done at the Department of Agricultural and Bioresources Engineering, Michael Okpara University of Agriculture, Umudike. The dryers were designed on force convection principle. The outlet vents were uniform (5mm radius). Energy was trapped and stored on a battery, which was used to power the blower. Trapping of the rays was enhanced by the surface of the collector which was painted with black oil paint. The collector aided transfer of heated air through the drying chamber. A door was fixed by the side of the drying chamber for easy loading and off-loading of the drying products. The wall of the drying chamber was covered with a transparent material. The dryers were operated by principles of forced convection, in which air was sucked and blown through the product in the dryer. The dryers had air inlet of various areas and shapes. The area of the collector was obtained as 2m<sup>2</sup>.

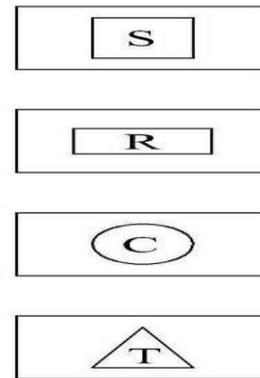


Fig.1: Shapes of the air inlet vent

### Legend:

- S – Air Inlet square design
- R – Air inlet rectangular design
- C – Air Inlet design circular
- T – Air inlet design triangular

Based on preliminary studies and size of the dryer a 12volts and 0.3A blower was selected for the dryer. The blower had a dimension of 12 by 12cm and was made of 5 blades. The solar panels available for experiment were three 150 Watts monocrystalline solar panels, which jointly gave a total available output power of 450 Watts.

The volumetric air flow rate of the dryer was computed from equation 1:

$$\text{Air flow rate, } Q = AV \text{ (m}^3/\text{s)} \quad 1$$

Where,

- Q = Volumetric air flow rate
- A = Length x Breadth (m<sup>2</sup>)
- Velocity of air at the point of inlet, V (m/s)

The drag force of the dryer was computed from equation 2:

$$F_D = \frac{1}{2} \rho V^2 A C_d \text{ (N)} \quad 2$$

- F<sub>D</sub> = Drag force (N)
- P = Density of Air (1.225 kg/m<sup>3</sup>)
- V = Velocity of air at the point of inlet, V (m/s)
- A = Air flow rate, Q = AV (m<sup>3</sup>/s)
- C<sub>d</sub> = Coefficient of drag (Dimensionless)

The experiment was designed to examine the effect of solar collector air inlet shape and product size on the performance of an active indirect mode solar dryer. The two independent variables considered are very important factors affecting the drying using an active direct mode solar dryer. The experimental design adopted was 2 factors, 5 levels, factorial Central Composite Rotatable Design (CCRD) of Response Surface Methodology, as adopted by Taheri-

Garavand *et al.* (2017), while optimizing the drying process of banana.

Central Composite Rotatable Design is comprised of three types of design points namely factorial points ( $n_f$ ), axial points ( $n_a$ ) and central points ( $n_c$ ). According to the Central Composite Rotatable Design, the total number of treatment combinations, was obtained from equation 3.

$$n = 2^k (n_f) + 2k(n_a) + k(n_c) \quad 3$$

where 'k' is the number of independent variables and n is the number of repetition of experiment at the center point. The total number of design points was obtained from equation 4.

$$N = 2^k + 2k + (n_o). \quad 4$$

Therefore, the CCRD involved 13 experiments consisting of  $2^2$  factorial CCD, with 8 axial points ( $\alpha = 2$ ) and 5 replications at the center points.

For each independent variable, the levels were chosen with respect to moisture content of cooking banana at harvest, preliminary experiments, observations and previous reports by various researchers on various solar dryers since there is no information as regards the optimization of the various drying parameters that influence the drying kinetics using an active direct mode solar dryer for cooking banana. The five levels used for each of the shape inlet are as captured in table 1.

Table 1: Levels of inlet shapes and areas considered for experimental design

S/N	Shape of Inlet	Dimension (cm)	Area (cm <sup>2</sup> )
S <sub>1</sub>	Square	2 x 4	4
S <sub>2</sub>	Square	4 x 4	16
S <sub>3</sub>	Square	6 x 6	36
S <sub>4</sub>	Square	8 x 8	64
S <sub>5</sub>	Square	10 x 10	100
R <sub>1</sub>	Rectangular	2 x 4	8
R <sub>2</sub>	Rectangular	4 x 6	24
R <sub>3</sub>	Rectangular	6 x 8	48
R <sub>4</sub>	Rectangular	8 x 10	80
R <sub>5</sub>	Rectangular	10 x 4	40
C <sub>1</sub>	Circular	Radius, R = 1	3.142
C <sub>2</sub>	Circular	Radius, R = 2	12.568
C <sub>3</sub>	Circular	Radius, R = 3	28.278
C <sub>4</sub>	Circular	Radius, R = 4	50.272
C <sub>5</sub>	Circular	Radius, R = 5	78.55
T <sub>1</sub>	Triangular	8 x 2	8
T <sub>2</sub>	Triangular	8 x 4	16
T <sub>3</sub>	Triangular	8 x 6	24
T <sub>4</sub>	Triangular	8 x 8	32
T <sub>5</sub>	Triangular	8 x 10	40



Fig.2: Experimental Site

### III. RESULTS AND DISCUSSION

#### Effect of air inlet area on air flow rate

The air flow rate, which is a key factor as regards optimization of the air inlet opening of the solar dryers were also computed as a function of air velocity and area of the inlet for respective shapes and corresponding dimensions. The values obtained were solely a function of the air inlet

area of the respective dryers. For the square shaped inlet dryers, the air flow rate ranged from 0.00277 to 0.024 m/s<sup>3</sup>. Dryer with air inlet area of 36 cm<sup>2</sup> gave an air flow rate of 0.0091 m/s<sup>3</sup>, while those that were of 100 cm<sup>2</sup>, gave an average air flow rate of 0.024m/s<sup>3</sup>. Figure 1 represents variation in air flow rate with air inlet dimension and product size for various air inlet shapes.

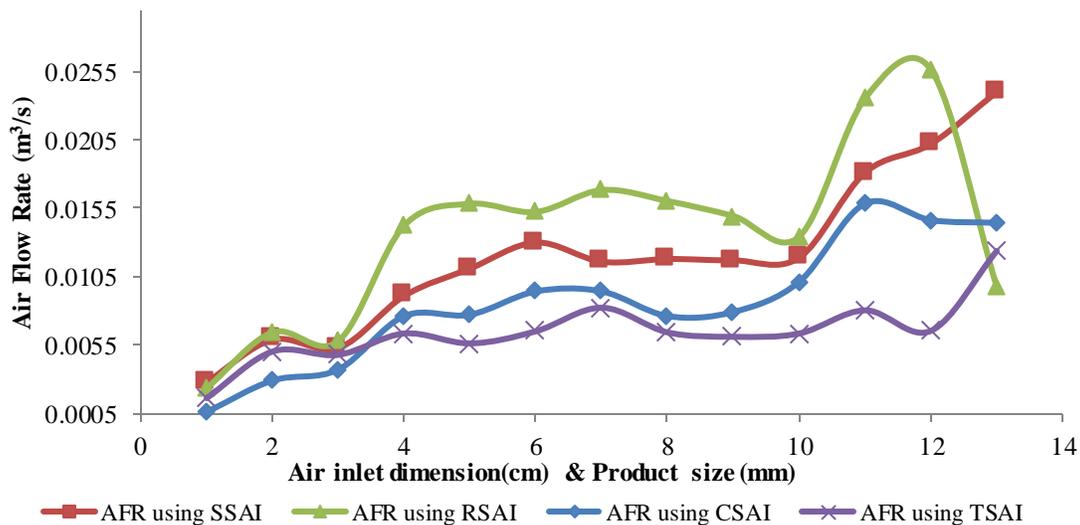


Fig.1: Variation in air flow rate with air inlet dimension and product size for various air inlet shapes

Where AFR is for Air Flow Rate and SSAI, RSAI, CSAI and TSAI represents Square Shape Air Inlet, Rectangular Shape Air Inlet, Circular Shape Air Inlet and Triangular Shape Air Inlet respectively.

The rectangular shaped inlet dryers recorded air flow rate ranging from 0.00232 to 0.0256 m/s<sup>3</sup>. These values showed increase of 6.25 % from what was obtained in square shaped inlet dryers. It was observed that the air flow rates of

dryers with 48 cm<sup>2</sup> air inlet area were in close proximity, as against those of lesser air inlet area. The air flow rate of the circular shaped inlet areas was also computed. It was observed that dryers of 28.278 cm<sup>2</sup> had the same air flow rate (0.0094 m/s<sup>3</sup>). This was the only similar scenario of the 52 dryers used for the experiment. The values obtained ranged between 0.0006 to 0.0158 m/s<sup>3</sup> for the 52 dryers. For the triangular shaped inlet dryers, the air flow rate for dryers ranged between 0.00163 to 0.0123 m/s<sup>3</sup>. The minimum value was less than what was obtained for square and rectangular shaped inlet dryers, but was about 65 % higher than that of circular shaped inlet dryers. The air flow rate of the respective dryer was dependent on the air velocity and the dimensions of the respective air inlet openings. Dryer of air inlet area 3.142 cm<sup>2</sup>, had the least air flow rate (0.0006 m/s<sup>3</sup>), the corresponding air inlet area was 12.568 cm<sup>2</sup>. Similarly, dryer of 80 cm<sup>2</sup> rectangular air inlet area had the highest air flow rate (0.00256 m/s<sup>3</sup>).

Onyinge *et al.* (2015) obtained a similar high air flow rate while designing and testing an indirect cabinet solar dryer for thin layer drying of *Rastrineobola argental* fish. A volumetric air flow rate of 0.00202m<sup>3</sup>/s was recorded. This value was in the range of what was obtained from the experiment (0.0006 to 0.0256 m<sup>3</sup>/s). Hedge *et al.* (2015) also reported high air flow rate in evaluating the performance of a solar dryer for banana. Khaldi *et al.* (2017) also observed that increasing the air inlet area

improved the drying process by reducing fluctuation in temperature and increased air flow by 18%. In the dryers constructed, it was observed that air flow increased at about 98% when comparing dryer with the smallest air inlet area to the highest. Zomorodian and Lamanian (2012) also reported high air flow rates while evaluating an innovative solar air collector with transpired absorber and cover.

**Effect of air inlet area on drag force**

The drag force was measured with aid of a blower. The blower sucked air from the inlet opening and the air passed through the products, thus enhancing the drying process and increasing the flow of air into the dryer. For the square shaped inlet dryers, the drag force ranged from 0.0008 to 0.0394 N. The values were so closely knitted. The air inlet area of dryers with 36 cm<sup>2</sup> air inlet area were the same. The rectangular shaped inlet dryers had its drag force range from 0.00412 to 0.0502 N. Figure 2 shows variation in drag force with air inlet dimension and product size for various air inlet shapes. The circular shaped inlet dryers had drag force values quite closer to each other. The least drag force was obtained as 0.000653 N, with an air inlet area of 28.278 cm<sup>2</sup>. The highest drag force of 0.0303 N corresponding to air inlet area of 50.272 cm<sup>2</sup>. The Drag Force computed was hugely dependent on the air inlet area and the air flow rate. Increase in area of inlet and air flow rate lead to corresponding increase in drag force.

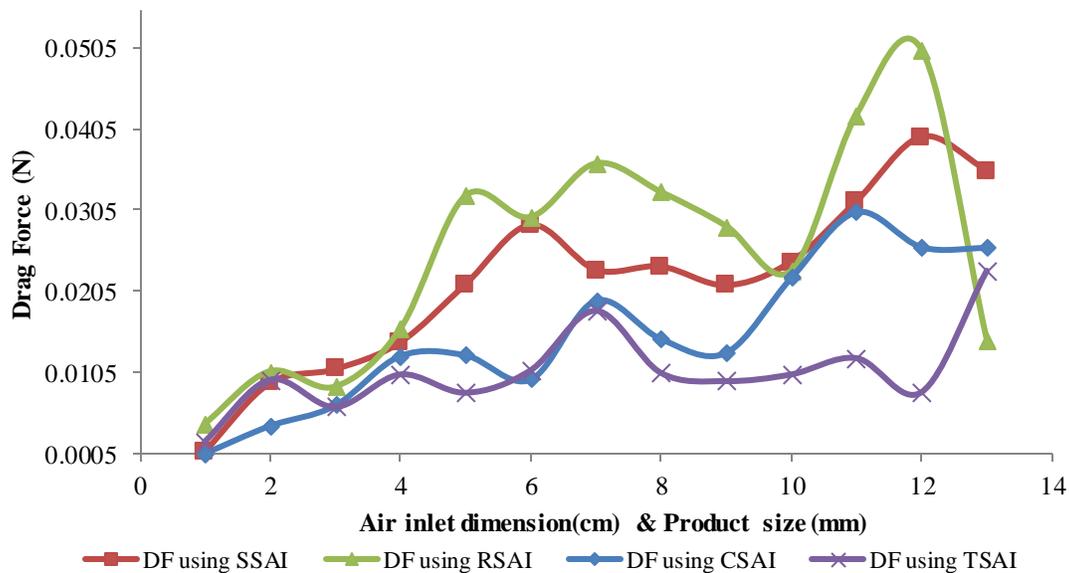


Fig.2: Variation in drag force with air inlet dimension and product size for various air inlet shapes

Where DF is for Drag Force and SSAI, RSAI, CSAI and TSAI represents Square Shape Air Inlet, Rectangular Shape

Air Inlet, Circular Shape Air Inlet and Triangular Shape Air Inlet respectively

For the triangular shaped inlet dryers, the drag force was obtained between 0.0021 to 0.023 N. These values were significantly less than that of square and circular shaped inlet dryers, but somewhat closer to that of the rectangular shaped inlet dryers. Dryers 43 and 49 had the same drag force (0.0103 N). Dryers with inlet area of 24 cm<sup>2</sup> had the same drag force. The rectangular shaped inlet dryers had the highest drag force, as compared to other. While the least value of drag (0.000653 N) was obtained for dryers with air inlet area of 48 cm<sup>2</sup>, while the highest values of 0.0502 N, was obtained for similar air inlet area.

#### IV. CONCLUSIONS AND RECOMMENDATIONS

The volumetric air flow rate of the square shaped inlet dryers ranged from 0.00277 to 0.024 m<sup>3</sup>/s. For the triangular and circular shaped inlet dryers, the air flow rate ranged from 0.00232 to 0.0256 m<sup>3</sup>/s and 0.000577 to 0.0158 m<sup>3</sup>/s respectively. The air flow rate of the circular shaped inlet dryer range from 0.00163 to 0.0123 m<sup>3</sup>/s. The values obtained were a function of the inlet area. The volumetric air flow rate of the dryer increased with increase in air inlet area. The values obtained ranged from 0.0006 to 0.0256 N. The air inlet area of an active indirect mode solar dryer should be increased based on the size of the dryer, to ensure efficient flow of air into the dryer, to fast track drying of cooking banana. The drag force of the square shaped inlet dryers was observed to range between 0.000827 to 0.0394 N, while those of the rectangular shaped inlet dryers ranged from 0.00412 to 0.0502 N. The drag force of the circular and triangular shaped inlet dryers ranged from 0.000653 to 0.0303 N and 0.00206 to 0.023 N respectively. These values were dependent on the area of the inlet and the air flow rate. The drag force increased with increase in air inlet area. The values obtained ranged from 0.0007 to 0.502 N, as the air inlet area increased across the various shape orientations. The air inlet area of an active indirect mode solar dryer should be increased based on size of the dryer, to enable the blower sufficiently drag air and circulate within the dryer for faster drying.

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