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ORIGINAL RESEARCH ARTICLE

SIMULATION OF PROTOTYPE ACTIVE AGRICULTURAL SOLAR DRYER WITH SLIT-TYPE TRANSPIRED SOLAR COLLECTOR

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ABSTRACT
This paper presents a functional and easy method for simulation of thin bed drying of maize in an active solar dryer with slit-type transpired collector using TRNSYS software. Thin layer solar drying model written in TRNSYS equation blocks in combination with existing components in the software library were used to build a solar mixed mode dryer system in TRNSYS environment for simulation. Experimental data for thin-bed solar dryer drying of maize obtained at different air mass flow rates of 0.026, 0.033, 0.034, 0.035 and 0.038 kg/sec, respectively, were used for model verification. There was good agreement between simulation results and experimental dryer temperatures for thin-bed solar dryer drying of maize with root mean square error (RMSE) and Nash- Sutcliffe efficiency coefficient (NSE) of 0.95, 0.57, 0.65, 1.15, 1.32 and 0.92, 0.93, 0.92, 0.85, 0.89 respectively for the air mass flowrates investigated. The results further confirmed that TRNSYS software can be a useful tool in the design and optimization of solar dryer systems.

1.0 Introduction

Drying of agricultural produce is a task that must be done due to the large amount of harvested agricultural produce which is impossible to consume immediately. Drying process is one of the most important components of postharvest handling of maize, therefore, a properly designed and operated dryer is an important feature of the maize value chain. Drying is defined as dual process of heat transfer to the product from the heating source and mass transfer of moisture from the interior of the product to its surface and from the surface to the surrounding air (Ekechukwu and Norton, 1999). Drying is the removal of moisture from the agricultural produce to prevent deterioration within a period of time regarded as the safe storage period for the purpose of preservation and to prevent the growth of micro-organisms such as enzymes, bacteria, yeast and moulds (Maame, 2014). The objective of the dryer is to supply the produce with more heat than is available under ambient conditions, increasing sufficiently the vapor pressure of the moisture held within the crop, thus enhancing moisture migration from within the crop and decreasing significantly the relative humidity of the drying air, thus increasing its moisture carrying capability and ensuring a sufficiently low equilibrium moisture content. In solar drying, solar energy is used as either the sole source of the required heat or as a supplemental source, and the air flow can be generated by either forced or natural convection. The heating procedure could involve the passage of the pre-heated air through the product, by directly exposing the product to solar radiation or a combination of both. The major requirement is the transfer of heat to the moist produce by convection and conduction from surrounding air mass at temperatures above that of the produce, or by radiation mainly from the sun and to a little extent from surrounding surfaces, or conduction from heated surfaces in conduct with the produce (Soteris, 2004).

The sun is the primary source of solar energy. The energy coming off the sun, called solar energy reaches us in the form of electromagnetic waves after experiencing considerable interactions with the atmosphere (Supranto et al., 2011). The radiant energy emitted or reflected by the constituents of the atmosphere forms the atmospheric radiation. The sun, which is 1.50 x 10^{11} m away, is a sphere of intensely hot gaseous matter with a diameter of 1.39 x10^9 m. The solar energy strikes our planet within 8 min 20 seconds after leaving the giant furnace. It has an effective black body temperature of 5762 K. In the central region, the temperature is much higher and it is estimated at 8 x 10^6 to 40 x 10^6 K. The sun's total output is 3.8 x 10^{20} MW which is equal to 63 MW/m^2 of the sun's surface. Solar energy radiates outwards from sun in all directions. Out of the total solar radiation emitted, the earth only intercepts a very small fraction of 1.7 x 10^{14} KW (Duffie and Beckman, 2013). It is estimated that 30minutes of solar radiation falling on earth is equal to the world energy demand for one year (Soteris, 2004). Every day the sun delivers 4.176x10^6 KWh. Muneer (2004) noted that one hour of solar energy that falls on earth is equivalent to one year world fuel consumption. Harnessing of solar energy can reduce fossil fuel consumption and reduce the CO_2 and CO emissions from heat engines.

Traditional open sun drying has been the most popular method of drying agricultural produce since the stone age to present age because it is simple and cheap. Sun drying for preservation of agricultural produce is as old as the creation of the world (Osman and Ertekyn, 2001). However, traditional open sun drying, which is regarded as direct sun drying, utilized widely by the rural farmers, has some disadvantages, such as requirement for large space, long drying time, crop damage by the hostile weather, contamination of grain from foreign materials, high crop losses as a result of inadequate drying, fungal attacks, insects, birds and rodents encroachment. Due to the problems of open sun drying, indirect solar energy cabinet dryers appear increasingly to be attractive as the best solution for the drying of agricultural produce. Indirect solar drying technology is becoming a better option to replace direct traditional open sun drying of agricultural produce because it is clean, hygienic and sanitary conditions to national and international standards (Samaneh et al., 2011). When comparing the direct traditional open solar dryers with indirect solar cabinet dryers, the later saves time, occupies less area, improves product quality and hygiene, makes the process more efficient and protects the environment (Bala and Woods, 1994).

Many researchers have designed, fabricated, tested and evaluated different types of solar dryers with different types of solar air heaters such as flat plate, parabolic and transpired. Most of the designers evaluated dryer with flat plate because of its simplicity, others improved it by using transpired plate with slit-like perforations. This study improved the transpired plate with slit-like perforations by reducing the depth of perforations and increases the effective area of heat transfer which in turn increases the rate of collisions of molecules, increase the temperature, gives strong jet impingement and better heat transfer. Lixin et al. (2014) validated glazed and unglazed transpired collector, the results show that the exit air temperature of glazed transpired collector (GTC) is higher than that of unglazed transpired collector (UTC) for a crosswind velocity

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exceeding 3.0 m/s with solar radiation of 400 W/m^2, ambient temperature of -10°C and suction velocity of 0.01 m/s. Bojia et al. (2014) validated glazed transpired solar collector with slit-like perforations, the simulated and experimental results were in good agreement with average deviation of 2.25 %. Wenke et al. (2017) validated the dynamic photovoltaic thermal collector (PVT) – solar air heater with fins (SAH) model under variable boundary condition and its performance was compared with an equivalent steady state model, the results show that the steady state model could overestimate the thermal energy gains of PVT – SAH system by 35 %. Zomorodian and Zamanian (2012) evaluated the effect of porosity and thickness on absorber performance of collector and the results show that the thermal efficiency of collector was increased as the porosity and the thickness increased. Samenah et al. (2011) compared the predicted and experimental data of temperature, humidity and moisture content on each tray of an indirect solar cabinet dryer, the simulated and experimental results agreed with each other. Kumar et al. (2009) discovered that the thermal efficiency of transpired solar collectors using jet impingement is found to be higher than other types of collector by about 10 – 20%. Xianli et al. (2016) discovered that GTC with slit-like perforated absorber plate maximize the effective heat transfer area of the absorber plate than UTC, thereby increase the thermal performance. In transpired absorber plate, the quality of the heat transfer coefficient and thermal efficiency were improved through effective strengthening of air that passes through the collector absorber when solar radiant heat and the heat between air and absorber were absorbed (Zomorodian and Zamanian, 2012).

TRNSYS energy modeling software is a powerful tool for designing, analyzing, and developing renewable energy systems (Aghbashlo et al., 2015). This energy simulation software has been deployed substantially and suitably for the study of solar thermal processes, building models and many other renewable energy technologies. The extreme flexibility of this software provides a suitable opportunity to simulate the performance of transient, ill-defined, and unforeseeable energy systems such as solar drying systems (Aghbashlo et al., 2015). There is very little information available in literature on simulation of maize solar drying using a mixed mode dryer with a transpired slit-type absorber air heater.

The main objective of this paper is to develop a TRNSYS simulation model for forced convection maize solar drying using a mixed mode dryer integrated with a transpired absorber air heater, and then validate the model using experimental drying data for five mass flow rates; 0.026, 0.033, 0.034, 0.035 and 0.038 kg/sec. The proposed method can be used for visualizing the dryer system and prediction of the solar dryer environment under different operating conditions.

2. Materials and Methods

2.1 Description of the dryer

The experimental set up as illustrated by Figures 1 and 2, was designed and fabricated to dry food crops and vegetables in Department of Mechanical Engineering, University of Agriculture, Makurdi, Nigeria. The solar drying experiments were carried out during the month of June 2017. Each test started at 09:00 am and continued till 15:00 pm. The drying of Maize was done in experimental field-type solar dryer made up of a 0.746 kW variable speed centrifugal fan, air heater, a drying chamber, a vent and the base structure. The variable speed centrifugal fan was used to blow air into the glazed transpired solar air heater through a square duct (50 mm × 50 mm) insulated with polystyrene insulating materials. The air-heater, through which the drying air is heated as it flows through the perforated absorber plate during solar drying mode, consists of a 0.5 mm thick absorber (1500 mm × 600 mm) with 518 slit-like perforations (37 rows by 14 columns) on a 0.5 mm aluminum sheet. The top surface of the aluminum absorber (1500 mm by 600 mm) is coated with black paint to maximize absorption of incident solar radiation. Ambient air is drawn into the plenum between the back plate and absorber plate; it passes through the slit-like perforated absorber plate into the plenum between the glass cover and absorber plate to the drying chamber. The sides and back plate of the air heater are made from wood particle board. The wood particle board is a poor thermal conductor, thereby serving as heat insulators for the air heater. The transparent top of the collector is a 1500 mm × 600 mm by 240 mm clear glass, to provide heating through the greenhouse effect. The drying chamber in which the maize to be dried has a dimension of 600 mm by 600 mm by 20 mm consisting of three trays and a rectangular frustum top made of 40 mm iron sheet with the side facing the sun coated in black for additional heating and a vent (Figure 3), through which the moist air is vented out. It houses three removable extended galvanized iron-mesh trays, arranged vertically in line on guides that are spaced 300 mm apart. The side walls are made up of wood particle board. There is a door that provides access to the chamber for loading, and unloading the maize grains.

Figure 1: Complete assembly of the experimental rig

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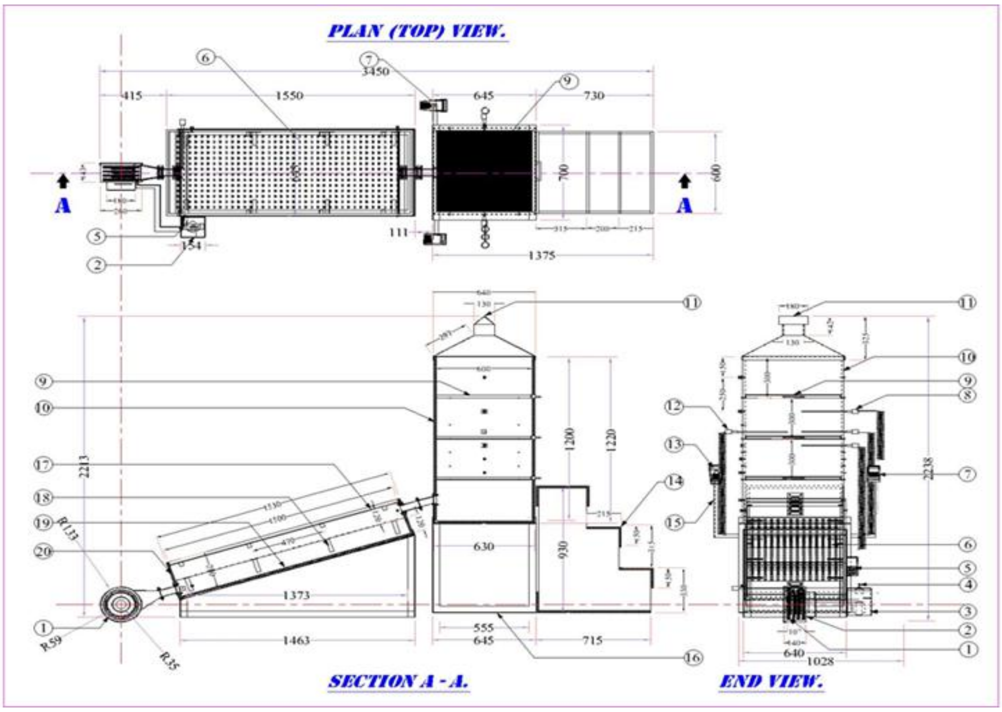

Figure 2: 1 Fan, 2 Blower fan housing, 3 Fan regulator casing, 4 Fan Regulator, 5 Solarimeter, 6 Transpired Absorber Plate 7 Thermocouple, 8 Thermocouple probe, 9 Trays, 10. Drying cabinet, 11 Vent, 12 Air flow probe,13. Air flow meter, 14 Stair case, 15 Probe hanger, 16 Frame, 17 Glass cover, 18 Absorber plate hanger, 19 Insulated lining, 20 Solar box collector

2.2 Validation of the model

In order to validate the model of the presented drying system using TRNSYS software, experimental data from a prototype mixed mode solar maize dryer integrated with a transpired absorber air heater (Akanji, 2019). Detailed information on the experimental solar mixed mode solar maize drying system integrated with a transpired absorber air heater, its design and data collection was presented by Akanji (2019). Data on solar drying of maize at different mass flowrates of 0.026, 0.033, 0.034, 0.035 and 0.038 kg/sec were used for model validation. The experiments were conducted in June, 2017, in Makurdi, Nigeria.

The root mean square error (RMSE) and Nash-Sutcliffe Efficiency Coefficient (NSE) was used to determine the level of deviation of the predicted result from the actual result. The root mean square error (RMSE) measures the quality of fit between the actual data and predicted model (Julien et al, 2013). The root mean square error (RMSE) of the model prediction with respect to the estimated variable X model is defined as the square root of the mean squared error (Neil, 2010)

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(X_{sim,i}-X_{exp,i})^2}{n}} \qquad (1)$$

where:

X_{exp} = experimental values

X_{sim} = simulated values

The lower the mean absolute error or bias percentage value, the better the performance of the model (Neil, 2010).

The Nash-Sutcliffe Efficiency Coefficient (NSE) is used to access the predictive power of hydrological models (Morasi et al., 2007). It is an indicator of the model's ability to predict about the 1:1 line between the observed (experimental) and predicted (modeled or simulated) values. Nash-Sutcliffe Efficiency Coefficient (NSE) is defined as;

$$NSE = 1 - \frac{\sum_{i=1}^{n}(X_{sim.i} - X_{exp.i})^2}{\sum_{i=1}^{n}(X_{exp.i} - X_{exp.i})^2} \quad (2)$$

Nash-Sutcliffe Efficiency Coefficient (NSE) can be used to quantitatively describe the accuracy of model outputs other than discharge. This method can be used to describe the predictive accuracy of other models as long as there is observed (experimental) data to compare with the model (simulated) results (Morasi et al., 2007). Nash-Sutcliffe Efficiency Coefficient (NSE) can range from $-\infty$ to 1. An Efficiency Coefficient values equal to 1 (E=1) indicate a perfect fit between observed (experimental) and predicted (simulated) values. An Efficiency Coefficient of zero (E=0) indicates that the model predictions are accurate as mean of the observed data, whereas an Efficiency Coefficient less than zero (E<0) occurs when the observed mean is better predictor than the model (Ibrahim, 2015).

2.2 TRNSYS Model

The mixed mode solar maize dryer integrated with a transpired absorber air heater was developed using a transient systems simulation (TRNSYS16.0) software, which is a quasi-steady-state computer simulation and analysis program. TRNSYS contains a standard library including various subsystem components currently used in thermal and electrical energy systems, as well as components to apply input variables of local weather data or other arbitrary time-dependent forcing functions and desired outputs of simulation results. All components have been programmed in FORTRAN language (Klein et al., 2007). A known output of a given component can be applied as input to itself or to any number of other components according to the actual structure of a system to accomplish a specified task. These components can be selected and interlinked in any optional manner to establish a system's model (Aghbashlo et al., 2015). The general structure of the solar drying system model for the five mass flow rates with two drying chamber trays in the TRNSYS environment is shown in Figure 2.

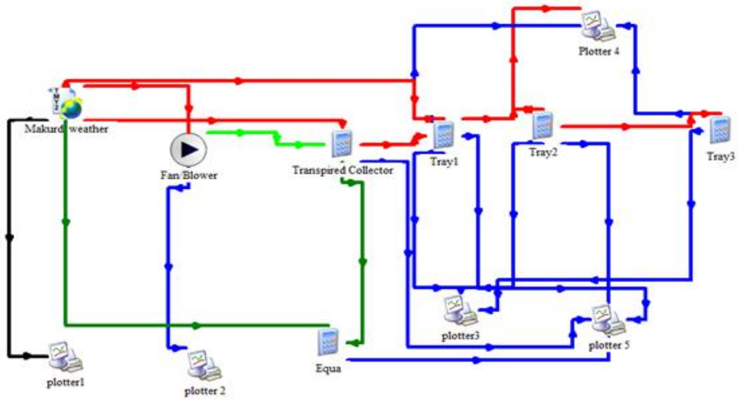

Figure 2: Structure of Transpired Solar Drying System Schematic Model in TRNSYS

3. Results and Discussion

Tables 1, 3, 5, 7 and 9 show the experimental and simulated results for temperature of trays obtained from rig and TRNSYS 16 Software (Type 109 TMY2 included in the solar weather data processor) for different days. Tables 2, 4, 6, 8 ad 10 show the validation of simulated results with experimental results of average drying temperature for all trays for different days using RMSE and NSE statistical tools.

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Table 1: Experimental and simulated results for temperature of trays obtained (0.026 kg/s)

TIME (hrs)	Tt1.sim (°C)	Tt1.expt (°C)	Tt2.sim (°C)	Tt2.expt (°C)	T3.sim (°C)	T3.expt (°C)
10.00	3.49E+01	36.9	2.95E+01	30.4	2.42E+01	25.9
11.00	3.67E+01	37.7	3.14E+01	32.5	2.61E+01	27.8
12.00	3.94E+01	38.9	3.41E+01	34.9	2.88E+01	29.0
13.00	4.22E+01	42.3	3.69E+01	36.7	3.16E+01	30.4
14.00	4.32E+01	43.5	3.79E+01	38.6	3.26E+01	32.9
15.00	4.32E+01	42.2	3.79E+01	37.8	3.27E+01	31.8

Table 2: Validation of simulated and experimental results of average drying temperature for all trays using RMSE and NSE (0.026 kg/s)

Time	TLsim	TLexpt	(TLsim - TLexpt)	(TLsim -TLexpt)^2	(TLexpt-TLexpt_ave)^2
10	3.49E+01	36.9	-2.0000	4.0000	11.2225
11	3.67E+01	37.7	-1.0000	1.0000	6.5025
12	3.94E+01	38.9	0.5000	0.2500	1.8225
13	4.22E+01	42.3	-0.1000	0.0100	4.2025
14	4.32E+01	43.5	-0.3000	0.0900	10.5625
15	4.32E+01	42.2	1.0000	1.0000	3.8025
Total	2.40E+02	241.5		6.3500	38.1150
Ave	3.99E+01	40.25			
RSME			1.0583		
NSE			0.8334		

Table 3: Experimental and simulated results for temperature of trays (0.033 kg/s)

TIME (hrs)	Tt1.sim (°C)	Tt1.expt (°C)	Tt2.sim (°C)	Tt2.expt (°C)	T3.sim (°C)	T3.expt (°C)
10.00	3.49E+01	35.7	2.96E+01	30.5	2.43E+01	25.0
11.00	3.62E+01	37.7	3.09E+01	30.3	2.56E+01	27.5
12.00	3.76E+01	38.2	3.23E+01	31.8	2.70E+01	27.7
13.00	3.87E+01	38.9	3.34E+01	32.9	2.81E+01	28.2
14.00	3.98E+01	40.8	3.45E+01	34.2	2.92E+01	30.6
15.00	4.07E+01	41.2	3.54E+01	34.9	3.01E+01	29.9

Table 4: Validation of simulated and experimental results of average drying temperature for all trays using RMSE and NSE (0.033 kg/s)

Time	TLsim	TLexpt	(TLsim - TLexpt)	(TLsim -TLexpt)^2	(TLexpt-TLexpt_ave)^2
10	3.49E+01	35.7	-0.7754	0.6012	9.3025
11	3.62E+01	37.7	-1.4554	2.1181	1.1025
12	3.76E+01	38.2	-0.6087	0.3706	0.3025
13	3.87E+01	38.9	-0.1787	0.0319	0.0225
14	3.98E+01	40.8	-1.0172	1.0347	4.2025
15	4.07E+01	41.2	-0.4986	0.2486	6.0025
Total	2.28E+02	232.5		4.4051	20.9350
Ave	3.80E+01	38.75			
RSME			0.7342		
NSE			0.7896		

Table 5: Experimental and simulated results for temperature of trays (0.34 kg/s)

TIME (hrs)	Tti.sim (°C)	Tt1.expt (°C)	Tt2.sim (°C)	Tt2.expt (°C)	Texit.sim (°C)	Texit.expt (°C)
10.00	3.94E+01	38.9	3.40E+01	34.1	2.87E+01	30.8
11.00	4.18E+01	42.3	3.65E+01	36.6	3.12E+01	31.2
12.00	4.42E+01	43.0	3.89E+01	40.2	3.36E+01	34.6
13.00	4.63E+01	46.7	4.11E+01	41.1	3.58E+01	35.5
14.00	4.81E+01	46.6	4.28E+01	42.9	3.75E+01	38.3
15.00	4.65E+01	45.1	4.12E+01	42.0	3.60E+01	36.8

Table 6: Validation of simulated and experimental results of average drying temperature for all trays using RMSE and NSE (0.034 kg/s).

Time	TLsim	TLexpt	(TLsim - TLexpt)	(TLsim -TLexpt)^2	(TLexpt-TLexpt_ave)^2
10	3.94E+01	38.9	0.4541	0.2062	23.6844
11	4.18E+01	42.3	-0.4527	0.2050	2.1511
12	4.42E+01	43	1.2224	1.4942	0.5878
13	4.63E+01	46.7	-0.3515	0.1236	8.6044
14	4.81E+01	46.6	1.4700	2.1610	8.0278
15	4.65E+01	45.1	1.4164	2.0063	1.7778
Total	2.66E+02	262.6		6.1962	44.8333
Ave	4.44E+01	43.76667			
RSME			1.0327		
NSE			0.8618		

Table 7: Experimental and simulated results for temperature of trays (0.035 kg/s)

Time (hrs)	Tti.sim (°C)	Tt1.expt (°C)	Tt2.sim (°C)	Tt2.expt (°C)	T3.sim (°C)	T3.expt (°C)
10.00	3.90E+01	38.1	3.37E+01	33.8	2.84E+01	29.6
11.00	4.11E+01	39.2	3.58E+01	35.9	3.05E+01	30.9
12.00	4.29E+01	41.9	3.76E+01	38.4	3.23E+01	32.0
13.00	4.48E+01	45.1	3.95E+01	42.2	3.42E+01	32.2
14.00	4.66E+01	44.9	4.13E+01	41.8	3.60E+01	35.1
15.00	4.50E+01	44.3	3.97E+01	40.3	3.45E+01	35.9

Table 8: Validation of simulated and experimental results of average drying temperature for all trays using RMSE and NSE (0.035 kg/s)

Time	TLsim	TLexpt	(TLsim - TLexpt)	(TLsim -TLexpt)^2	(TLexpt-TLexpt_ave)^2
10	3.90E+01	38.1	0.9189	0.8444	17.2225
11	4.11E+01	39.2	1.9262	3.7104	9.3025
12	4.29E+01	41.9	0.9682	0.9375	0.1225
13	4.48E+01	45.1	-0.2855	0.0815	8.1225
14	4.66E+01	44.9	1.6943	2.8708	7.0225
15	4.50E+01	44.3	0.7193	0.5173	4.2025
Total	2.59E+02	253.5		8.9619	45.9950
Ave	4.32E+01	42.25			
RSME			1.4937		
NSE			0.8052		

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Table 9: Experimental and Simulated Results for Temperature of Trays (0.036 kg/s)

Time (hrs)	Tt1.sim (°C)	Tt1.expt (°C)	Tt2.sim (°C)	Tt2.expt (°C)	T3.sim (°C)	T3.expt (°C)
10.00	3.93E+01	38.3	3.40E+01	32.6	2.87E+01	29.2
11.00	4.26E+01	41.5	3.73E+01	37.0	3.20E+01	33.5
12 .00	4.57E+01	44.5	4.04E+01	41.8	3.51E+01	36.2
13.00	4.88E+01	47.4	4.35E+01	44.2	3.82E+01	37.9
14.00	4.77E+01	48.3	4.24E+01	42.7	3.71E+01	36.3
15.00	4.37E+01	43.9	3.84E+01	37.6	3.31E+01	34.3

Table 10: Validation of simulated and experimental results of average drying temperature for all trays using RMSE and NSE (0.036 kg/s)

Time	TLsim	TLexpt	(TLsim - TLexpt)	(TLsim -TLexpt)^2	(TLexpt-TLexpt_ave)^2
10	3.93E+01	38.3	1.0171	1.0345	32.3003
11	4.26E+01	41.5	1.1259	1.2677	6.1669
12	4.57E+01	44.5	1.1956	1.4294	0.2669
13	4.88E+01	47.4	1.4190	2.0136	11.6736
14	4.77E+01	48.3	-0.6361	0.4047	18.6336
15	4.37E+01	43.9	-0.2278	0.0519	0.0069
Total	4.46E+01	263.9		6.2018	69.0483
Ave	4.46E+01	43.98333			
RSME			1.0336		
NSE			0.9102		

Figures 3, 4, 5, 6 and 7 show the comparison of hourly average drying temperature for all trays recorded experimentally with the simulated values from TRNSYS 16 software for different days plotted in MATLAB 2009b. The results of RMSE and NSE for mass flow rates; 0.026, 0.033, 0.034, 0.035 and 0.038 kg/sec. are 1.06, 0.73, 1.03, 1.49, 1.03 and 0.83, 0.79, 0.86, 0.81, 0.91 respectively. The simulated data acceptably agreed with experimental data for both inlet drying air and outlet moist air.

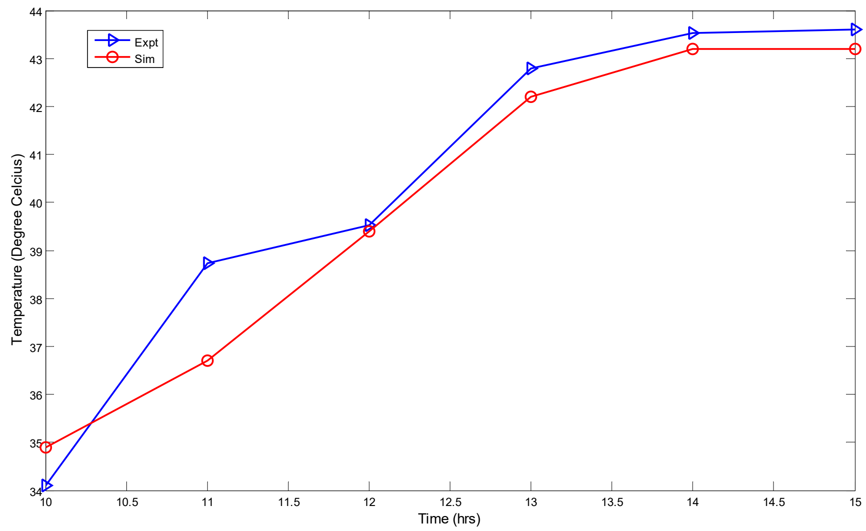

Figure 3: Comparison of experimental and simulatedhourly average drying temperature for all trays recorded with the predicted values (0.026 kg/s)

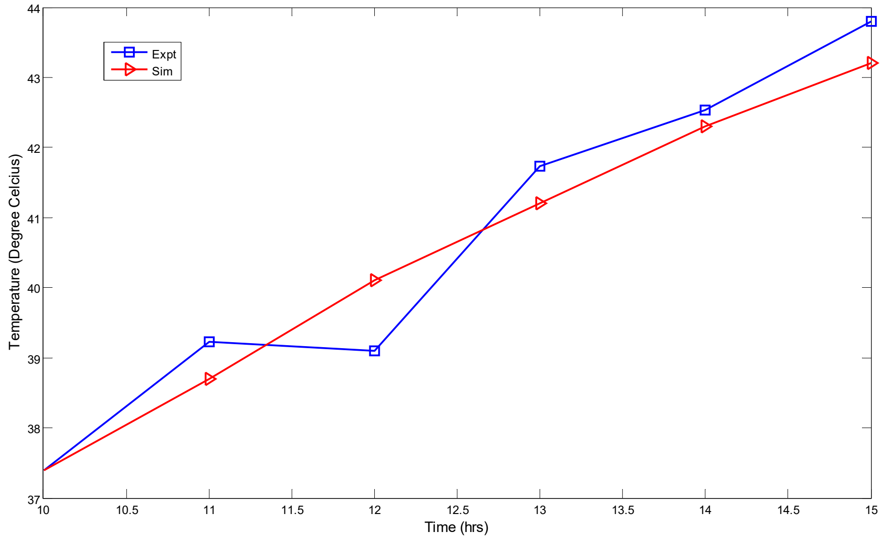

Figure 4: Comparison of experimental and simulatedhourly average drying temperature for all trays recorded with the predicted values (0.033 kg/s)

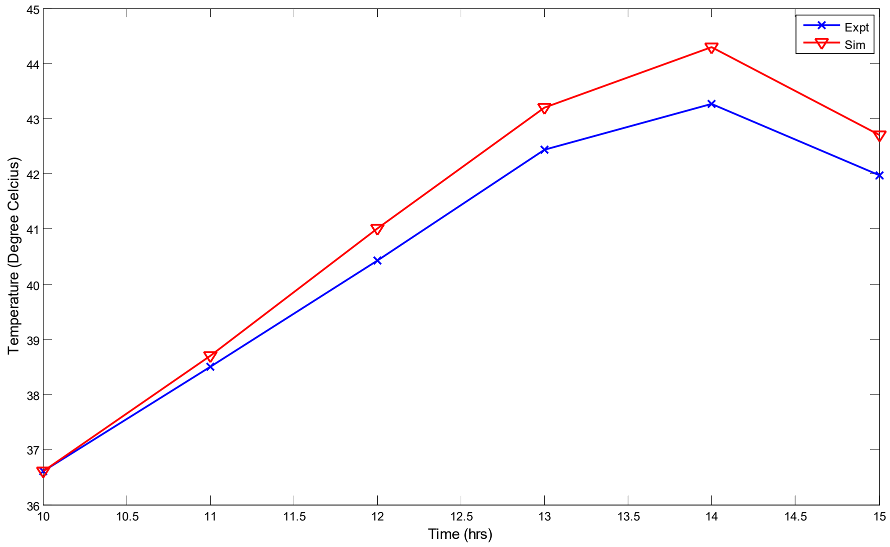

Figure 5: Comparison of experimental and simulated hourly average drying temperature for all trays recorded with the predicted values (0.034 kg/s)

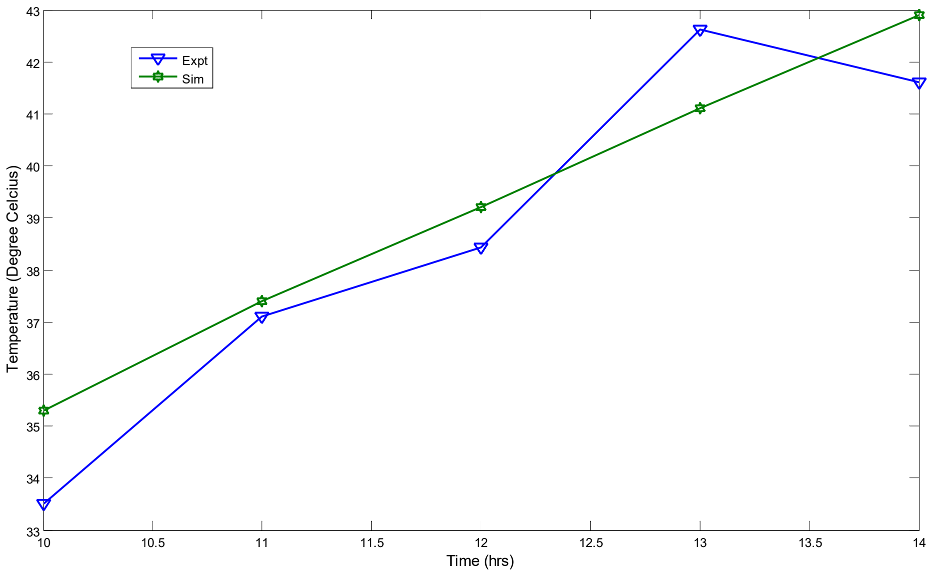

Figure 6: Comparison of experimental and simulated hourly average drying temperature for all trays recorded with the predicted values (0.035 kg/s)

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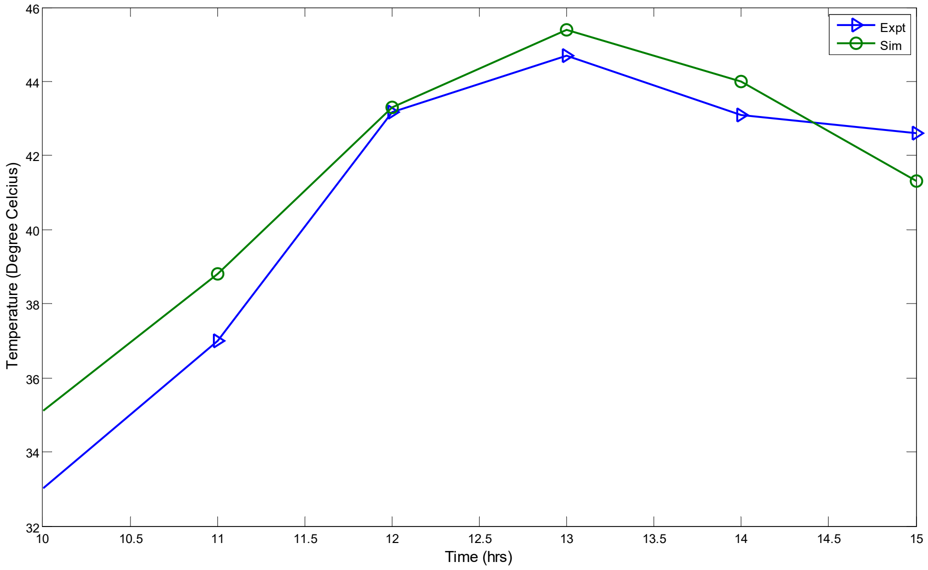

Figure 7: Comparison of experimental and simulated hourly average drying temperature for all trays recorded with the predicted values (0.036 kg/s)

The RMSE values imply that the error between the mean of the experimental drying chamber temperature are 1.06, 0.73, 1.03, 1.49 and 1.03 for five different days. The NSE values of 0.83, 0.79, 0.86, 0.81 and 0.91 indicate a good quality of fit between the experimental data and predicted data from the model. Therefore, good model predictive powers as the NSE values are positive and approaches 1. The simulated data fittingly tracked the experimental drying air temperature. The digression between experimental and TRNSYS solar radiation data could have a significant role in the difference between experimental and simulated drying air temperatures (Aghbashlo et al., 2014)

5. Conclusion

A TRNSYS model was developed for simulation of dryer conditions in thin layer drying of maize by integrating a mathematical model of a mixed mode solar dryer with transpired slit-type absorber for air heating. The validated TRNSYS model can be used to simulate conditions of solar-drying systems in different locations predict system condition under different operating conditions. The advantage of applying this approach is that the solar dryer operation can be visualized and tinkered as much as possible without actual construction and test running in the preliminary design phase. This will eliminate a huge cost at the design and optimization phase.

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