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Experimentation and modeling dehumidified air dryer

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ABSTRACT

Drying process assessment depends on several complex physical phenomena. This paper develops dehumidified air dryer modeling in order to determine the humidity rate releases over time and drying period. Firstly, experimental dehumidified air dryer devices much with sensors were built to vaporize 5ml of water under atmospheric condition. Then, modeling based on heat and mass transfers using Colburn's analogy with Gnielinski correlation was applied to evaluate vapor rate. Model input data use temperature, humidity and air velocity measured from censors during experimentation. As results, model shows similar trend diagram of vapor rate and drying period with experimentation. According to the model, 6690s is needed to dry 5ml of water whereas experiment shows only 5700s which represents 15.17% of an error. Under the same conditions, open air drying process takes considerably more time to dry up equivalent amount of water. Knowing vapor rate to dehydrate from various products, dehumidified air dryer model can be a useful tool to predict drying period.

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1. INTRODUCTION

Drying process is a method used to preserve food products. Depending on the variety of products to be dried, many types of dryers exist, some of which are more or less efficient in mechanical dryers or chemical dryers. Air-dried or naturally dried products have a long drying time. To overcome this issue, artificial drying was invented. This type of drying can reduce significantly drying period compared to natural drying process.

Theoretical and experimental studies have been carried out by researchers to improve the performance and speed of drying process. In 1993, there was the experimental determination of the drying rate of a medicinal plant "Centella Asiatica" [1], the experimental determination of the internal mass transfer coefficient of tanned leather in 1993 [2] and the establishment of models of thin-film drying rates of pineapple and pozzolan in 1993 [3]. And in 1985, a multi-purpose modular indirect solar dryer was built [4].

This study focus on the open-air dryer, more specifically the dehumidified in carrying out an experiment and building mathematical model to simulate drying process. The purpose is to evaluate and compare the drying period using the combined heat and mass transfer methods.

2. DESCRIPTION AND CHARACTERISTICS OF THE DEHUMIDIFIED AIR DRYER

Figure 1 shows the dehumidified air dryer. It is made up of a rectangular plywood tube 2cm long and 8cm wide having air dehumidification device made of conical sheet, 2mm thick, laid longitudinally on its inlet.

In the experiment, the mini-dryer is placed 0.5m from the ground and has very thin thickness aluminum tank filled with water, 7.8cm long and 7.8cm wide. To supervise the evolution of the physical parameters during the experimentation in dryer chamber, two DHT22 sensors at the inlet and outlet to measure temperature and humidity and an anemometer to measure the air speed placed at the outlet. These censors ensure the parameter measurement every 30s. Some of these parameters are among the input parameters of modeling.

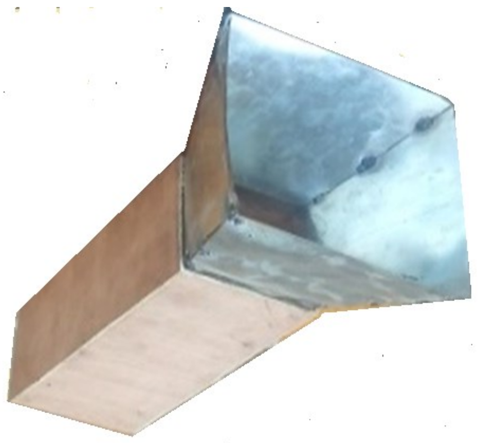

Figure 1: Dehumidified air dryer

3. PHYSICAL PHENOMENA IN THE MINI-DRYER

The mini-dryer lays number complex physical phenomena generated mainly by a chemical potential gradient or concentration and a temperature gradient. The phenomena responsible for drying with dehumidified air are:

- mass transfer of water vapor,
- transfer by conduction in the walls,
- convective transfer between walls and air indoors, outdoors and between water and dehumidified air,
- radiation transfer between interior walls.

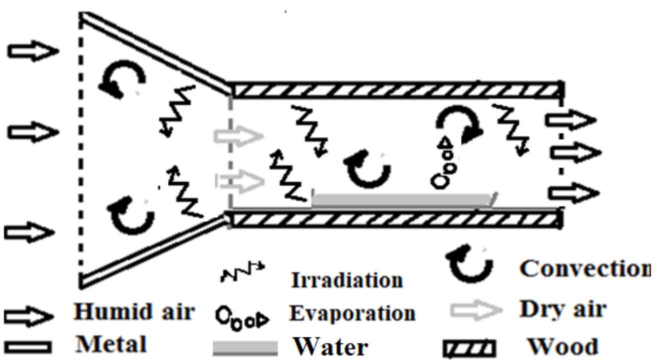

Figure 2: Mass and heat transfers of the mini-dryer

3.1. Mass transfer of water vapor

The mass transfer of water vapor generates evaporation from the tank and water vapor exchange in the air. The friction of dehumidified atmospheric air sweeping over the water ensures the evaporation of water from the drying chamber. Air friction is supposed 10,000 times that the water vapor friction. This water then supposed to have a homogeneous temperature.

Water vapor exchange between air and the water in the tank depends on the gradient of concentration between these two areas. Water vapor concentration in an area depends on the phenomena of mass diffusion across the surface.

3.2. Conduction transfer in the walls

Heat transfer by conduction takes place through the walls of the chamber. Each material of the dryer walls is characterized by its conduction coefficient, specific heat, density. For plywood and sheet metals, these parameters are given in Table 1 [5].

Materials	Specific heat (J $kg^{-1}K^{-1}$)	Density (kg m^{-3})	Conductivity coefficient ($Wm^{-1}K^{-1}$)
Plywood	1880	300-600	0.15
Sheet metal	380	7200	110
Aluminum Plate	897	2700	237

3.3. Convective transfer between walls and air

Convective exchanges are formulated by Newton's relation making the parameter h_{ve} what is called the convective exchange coefficient, which depends mainly on the geometry and nature of the bodies in exchange. There are several correlations to evaluate this coefficient. Since the air velocity V_v varies between 0 and 2 m s^{-1} inside dryer chamber, the interior and exterior convections between the walls and the external environment are determined with the convective coefficient h_{ve} given by HOTTEL and WOERTZ [5]:

$$h_{ve} = 5.67 + 3.86\, V_v \quad (1)$$

3.4. Radiation transfer between walls

Radiation transfer between walls indicates the energy emitting or absorbing process of electromagnetic waves. Thermal radiation is an energy transfer characterized by wavelengths between 10 and 1000nm. Besides heat conduction and convection in the mini-dryer, hot wall equilibrium is result of irradiative exchange with other walls.

1.MODELING OF THE MINI-DRYER

4.1 Hypotheses

Fluid air flows in the mini-dryer to generate heat and vapor transfers. Thus, the air dehumidification part does not enter into the mini-dryer modeling. Since the drying time in the experiment lasts less than 2 hours to dry a quantity of water of 5ml in the water tank, the following assumptions are adopted:

- vapor condensation is negligible,
- dehumidified air pressure inside the dryer is equal to atmospheric pressure,
- ambient air and dehumidified air behave like a perfect gas,
- air velocity at the inlet and outlet of chamber dryer is uniform,
- thermal influence of the wall on the boundary of the dryer outlet is assumed to be negligible,
- water tank and water form thermally thin body having uniform temperatures
- radiation effect inside dryer chamber is negligible.

1.2. Colburn's analogy

Colburn's analogy allows evaluating mass transfer rate in a system where change in flow and temperature exists, as in the mini-dryer. It can be used when Schmidt dimensionless number varies between 0.6 and 60 and the airflow is 10,000 times greater than the water vapor flow. Gilliland-and Colburn experimental law established the equation:

$$Sh = 0.023 Re_L^{0.83} Sc^{0.44} \quad (2)$$

$$Nu = 0.022Re_L^{0.83}Pr^{0.83} \tag{3}$$

1.2.1. Reynolds number

Reynolds number is a dimensionless number used in fluid mechanics. It can characterize the nature of flow whether laminar, transient or turbulent regime in the mini-dryer [6].

$$Re_L = \frac{V_v\,L}{\nu_d} = \frac{\rho_d V_v L}{\mu_d} \tag{4}$$

where
ν_d : kinematic viscosity of the dehumidified air (m^2s^{-1})
V_V: dehumidified air velocity ($m\ s^{-1}$)
ρ_d : dehumidified air density at the infinity of the water film free surface ($kg\ m^{-3}$)
μ_d: dehumidified air dynamic viscosity (Pas^{-1})
L : length of tank (m)

1.2.2. Schmidt Number

The Schmidt number is a dimensionless number that represents the ratio of V_d momentum diffusivity (or kinematic viscosity) to mass diffusivity. It is used to characterize fluid flows in which viscosity and matter transfer are simultaneously involved [7]. For the mini-dryer, it is defined as follows:

$$\mathrm{Sc} = \frac{\nu_d}{D_{vap}} \tag{5}$$

Prandtl Number

The Prandtl Number is a dimensionless number approximating the ratio of momentum diffusivity to thermal diffusivity. It can be expressed as

$$Pr = \frac{\nu_d}{\propto} = \frac{\mu_d C_p}{k} \tag{6}$$

where
ν_d : momentum diffusivity of air (m^2s^{-1})
$\propto$: thermal diffusivity of vapor (m^2s^{-1})
μ_d :absolute or dynamic viscosity of air (kg m^{-1} s^{-1})
C_p: specific heat of water ($J\ kg^{-1}\ K^{-1}$)
k : thermal conductivity (W m^{-1} K^{-1})

The Prandtl Number is often used in heat transfer and free and forced convection calculations. It depends on the fluid properties.

4.3.2. Convection heat coefficient

To evaluate convection heat coefficient, Lewis proposed the following function to characterize mass transfer by heat transfer:

$$\frac{Sh}{Nu} = L_e^{\frac{1}{3}} = \left(\frac{Sc}{Pr}\right)^{\frac{1}{3}} \tag{7}$$

and

$$F(Le) = \frac{h}{h_m\rho C_p} \tag{8}$$

The convection heat coefficient h expressed with Nusselt number gives,

$$h = \frac{\mathrm{Nu}\lambda_d}{L} \tag{9}$$

where λ_d : thermal conductivity of the dehumidified air in ($m^{-1}K^{-1}$).

4.3.3. Mass transfer coefficients

First, relationship between the mass convective exchange coefficient and the convective heat exchange coefficient exists,

$$\frac{h}{h_m \rho_d C_p} = (\frac{Sc}{Pr})^{\frac{2}{3}} \tag{10}$$

The Sherwood number can also be written as:

$$Sh_L = \frac{h_m L}{D_{vap}} \tag{11}$$

Finally, this implies the convective mass transfer coefficient:

$$h_m = \frac{Sh_L D_{vap}}{L} \tag{12}$$

4.4. Gnielinski correlation

Gnielinski correlation is a very complex correlation for tubes like the mini-dryer. It is valid over a wide range of Reynolds numbers, including the transition region For the Prandtl number varies between: 0.5 ≤Pr≤ 2000 and the Reynolds number between$3000 \le Re_L \le 5.10^6$, this correlations is written as [9]:

$$Nu_L = \frac{\left(\frac{f}{2}\right)(Re_L - 1000)}{1 + 12.7 \left(\frac{f}{8}\right)^{\frac{1}{2}} (Pr^{\frac{2}{3}} - 1)} \tag{13}$$

Where the Darcy friction factor can be expressed in a function of Reynolds number between $8000 \le Re_L \le 30000$ [9]:

$$f = 0.316\, Re_L^{-\frac{1}{4}}$$

This leads to the determination of the simultaneous convective heat flux and mass flux:

$$(\rho\, C_p\, (\frac{\alpha}{D_{vap}})^{2/3})\ (T_p - T_d)\ = (\rho_v - \rho_d) \tag{14}$$

4.5. Method of calculation of water vapor mass

4.5.1. Simultaneous convective heat flux and mass transfer

Taking into account the adopted hypothesis, only evaporation caused by diffusion and heat exchange remains to be considered in the model formulation. Simultaneous convective heat flux and mass transfer can be written as:

$$h(T_w - T_d) = h_m(\rho_v - \rho_d) \tag{15}$$

where

h: convective heat exchange coefficient in $m^{-2}K^{-1}$

h_m : mass convective exchange coefficient (ms^{-1})

T_d: temperature of the dehumidified air to infinity (K)

T_w: water surface temperature (K)

ρ_v: water vapor density at the water film surface($kg.m^{-3}$)

ρ_d : density of the dehumidified air at infinity of the free surface of the water film(m^2K^{-1})

4.5.2. Water vapor mass calculation

The mass flow of the wetted surface with water film of the plate is characterized by the substitution of a mass transfer coefficient $h_m$for the density of diffusion fluxes, such as:

$$\dot{m}_v = h_m(\rho_v - \rho_d)S \tag{16}$$

Since dehumidified air and water vapor assumed like perfect gas,

$$\frac{\rho_v}{M_v} = \frac{P_{vp}}{RT_d} \tag{17}$$

and

$$\frac{\rho_d}{M_d} = \frac{P}{RT_d} \tag{18}$$

where

M_v: molar mass of water vapor (M_v=18g mol^{-1})
M_d: molar mass of dehumidified air (M_d≈29g mol^{-1})

Finally, the mass of vapor M_{vap} during time step Δt

$$M_{vap} = \dot{m}_v \, \Delta t \tag{19}$$

4.6. Resolution method

The model resolution method determines the drying time period (t_s). This model consists of several steps according to the flow chart in Figure 3.

First, after declaring the physical parameters, some parameters are initialized including the initial mass of water to dry up M_t which is 5ml and physical parameter data measurement obtained from sensors such as air speed, humidity h_{in} and temperature t_{in}. Then, the physical properties of air and water vapor are calculated, followed by the determination of different dimensionless numbers.

Then, the exchange coefficients, the saturation vapor pressures in the air, the density of water vapor, the mass flow of water vapor and the mass of water vapor are calculated, which is the rate of vapor evaporated at each time step 30 seconds. And then, cumulate mass of water vapor every 30 seconds is calculated in order to have the sum of total quantity of water vapor (M_{vap}) during drying process.

For the stop criterion, as long as the mass of evaporated water (M_{vap}) is still less than the initial mass (M_t), the operation continues, otherwise the calculation stops. Finally, at the end of the calculation, the drying time period t_s and the quantity of vapor accumulation are displayed.

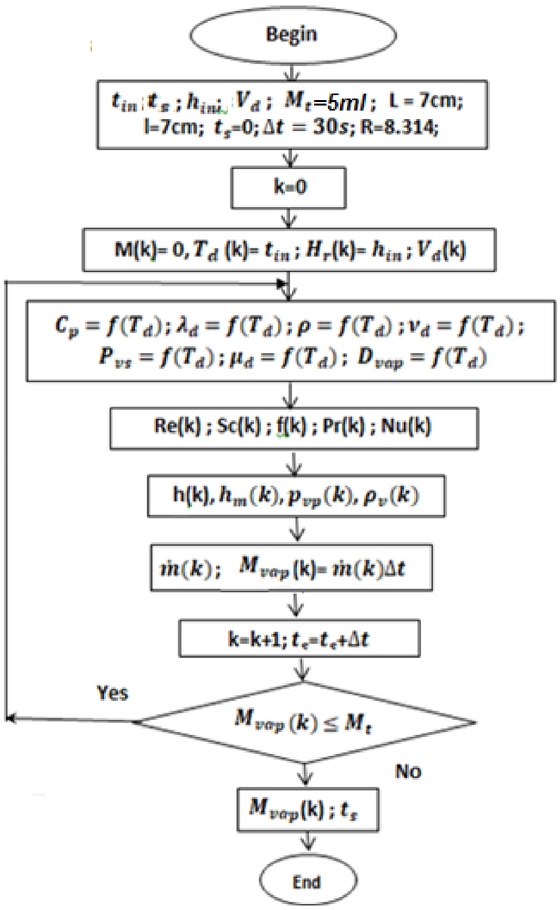

Figure 3: Flow chart of the drying modeling

5. RESULTS

5.1. Air speed in the mini dryer

During experimentation, 5ml of water to dry placed in the tank located in drying chamber. An anemometer placed at the entrance of the mini-dryer measures dehumidified air velocity V_d circulating in the drying chamber which varies between $0.4ms^{-1}$ and $2.8ms^{-1}$ (Figure 4). This air velocity, used as input parameter in the model, plays an important role in the drying process.

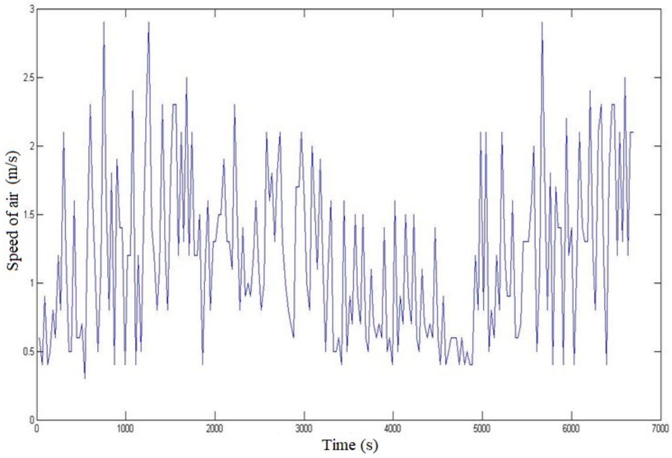

Figure 4: Variation of air speed at the entrance of the mini-dryer

5.2. Dehumidified air temperature

Figure 5 shows air temperature variation measured in the dehumidified mini-dryer. Drying process stops when both inlet and outlet temperatures look similar. Pattern diagram exhibit three different areas:

- Time [0s-800s [: the temperature variation diagram of the air at the inlet and outlet of the drying chamber are almost the same trend. In this range, heat transfer between the drying air and the water start to generate vapor above the liquid water. Temperature of the liquid water is still in equilibrium with air.

- Time [800s-5700s [: due to evaporation, this domain shows gap between air temperatures t_{out} and t_{in}. Heat and mass transfer increase significantly between dehumidified air and water.

- Time [5700s-6690s [: temperatures t_{out} gradually increase to reach t_{in} temperature. This range indicates the drying time about 5700s. It means the water disappears completely as the air attains hygrometric balance.

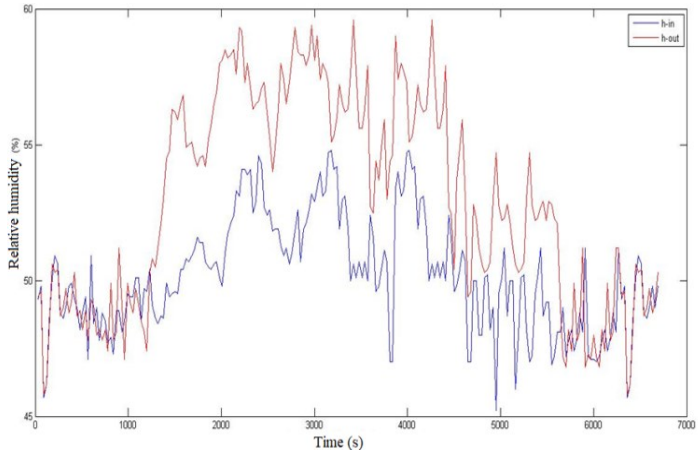

Figure 5: Air inlet and outlet temperatures variations in dryer chamber

5.3. Air humidity in the mini-dryer

Air humidity at the inlet and outlet of dryer chamber obtained from humidity sensor measurements varies along the temperature. The drying process ends when the gap between inlet and outlet humidity completely disappears. The variation of the humidity the dehumidified air dryer to dry up 5ml of water divides in three distinct areas (Figure 6):

- time 0-1000s, the inlet and outlet humidity are almost similar due to absence of mass transfer exchanges. At this area, the saturation vapor pressure of the water surface remains lower than the partial vapor pressure in the dehumidified air. Indeed, after 1000s, convective transfer is the only phenomenon that activates the vaporization of the water almost negligible because the saturation vapor pressure in the dehumidified air becomes equal to the saturation vapor pressure.
- time 1000-3800s, the humidity of the air h_{out} increases considerably due to the evaporation of the water from the tank. This mass transfer, due to the difference in the partial pressure of water vapor at the surface of the water and the partial pressure of water vapor in the dehumidified air, is combined with the convective transfer caused by the difference in the inlet and outlet temperatures
- time 3800-4150s, the humidity of the air at the h_{out} outlet tends towards the humidity at the inlet of the mini-dryer. Indeed, water in tank vaporizes slowly until it dries out or the partial pressure gradient of water vapor at the inlet and outlet of the mini-dryer run out.

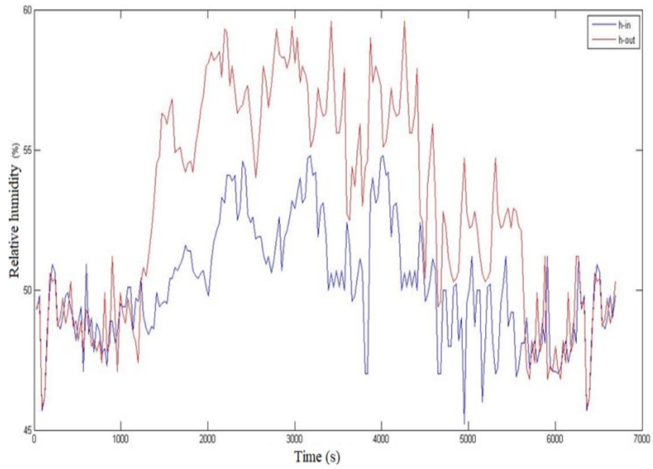

Figure 6: Air humidity variation at the inlet and outlet of the dryer for water drying

According to Figure 5, the rising temperature gradient leads to humidity increase. The mini-dryer is placed in the open air where the air speed fluctuates incessantly (Figure 4).

5.4. Result of the numerical model

Mini-dryer model uses data from sensors air speed V_d , Temperature t_{in} and the humidity h_{in} of the dehumidified air as input parameter. In each time space Δt, it calculates cumulative volume of water vapor M_{vap}. According to the result from modeling, it takes about 6690s or 1h 52mn to dry 5ml of water in the water tank (Figure 7).

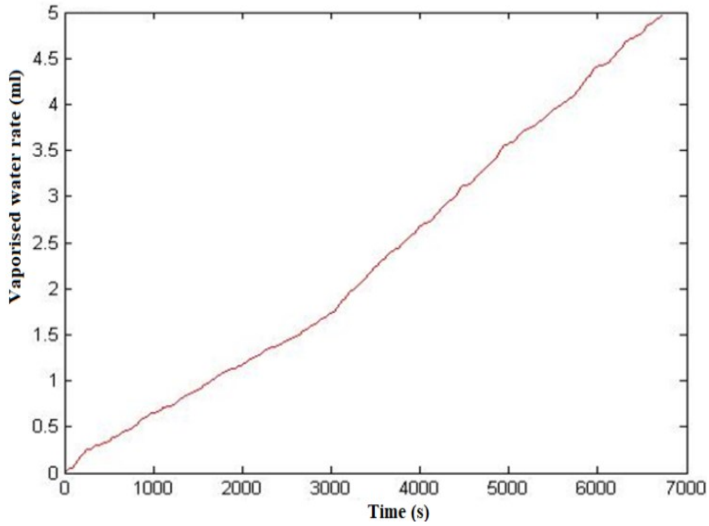

Figure 7: Cumulative volume of water vapor vaporized in the mini-dryer

5.5. Comparison of measurement results and model

The comparison of drying time by the modeling and experimentation is necessary to know its accuracy.

Table 2 compares the drying period from both values.

Table 2: Comparison of water drying times

	Modeling	**experiment**	**difference**	**Error**
Drying period	1h52mn (6690s)	1h 35mn (5700s)	17mn (990s)	15.17%

According to the table, apparently model underestimates drying period compared to the experiment with 17 minutes absolute error. This error is probably due to:

- DHT22 sensor sensitivity, 2% accuracy for humidity and 0.5°C for temperature
- air speed of the anemometer with 2%accuracy,s
- influence of the air property outside the dryer.
- sensor location at the inlet and outlet of the dryer may affect the measurement.

6. CONCLUSION

Dehumidified air dryer modeling makes it possible to understand mass transfer phenomenon related to dehumidified air and to validate theories related to it. A mini-dryer much with temperature, humidity and air speed sensors were designed for experimental measurements. A mathematical model based on hypothesis to quantify the water vapor exchanged between water and dehumidified air is developed in order to determine the drying period. In this model, the vapor transfer is deduced by the Colburn analogy and Gnielinski correlation. The evaluation of evaporated water vapor leads to determine drying period.

Drying period given by the model is 1h52m whereas experimental measurement gives 1h35mn. Model represents 15.17% accuracy. The sensors sensitivity used and their location during experiment combined with assumptions in the model may cause this difference. Knowing quantity of water in product, model can predict drying period whis is relatively rapid in this mini-dryer compare to natural open air air process.

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