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Study and Characterization of Air Flows During Intermittent Drying

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Abstract- This work presents the study and characterization of the airflows during the intermittent drying of a local variety of mango from the Adamawa Region. The experimental study was carried out in a modular electric forced convection dryer. Three air drying temperatures, an air velocity (1.37 m/s) and two initial masses of mango samples were the conditions selected of drying process. The duration of the drying cycle was set at 120 minutes and the intermittency α was taken as the ratio between the drying time at the drying air temperature and the total duration of a cycle. Analysis of the curves showed that during vacuum drying, for an operating time of the dryer of 210 minutes, the air relative humidity inside the drying chamber was 48.9; 40.6 and 19.7% respectively for α = ¼, ½ and ¾, at the respective temperatures of 40; 50 and 60°C. During the load tests, the airflow rate in the drying chamber was turbulent. Drying with α = ¾ allowed to have better drying performance for an initial mass of 500g, against a mass of 800g causes a rapid rise in the air drying relative humidity inside the drying chamber which prolongs the drying time comparatively.

Keywords:- Air flow; Intermittent drying; Forced convection; Mango; Through flow.

I. INTRODUCTION

The west tropical zone is characterized by a high hygrometry of the air and a high rainfall (Edoun et al., 2010). It is also the place par excellence for agricultural products (fruits and vegetables) which occupy nearly 70% of the population (Kuitche et al., 2006). But more than 40% of post-harvest losses for these products are estimated (Tetang, 2018; Edoun et al., 2014; Bala et al., 2003). It is therefore necessary to find a means of conservation of these products to ensure their availability throughout the year on the one hand and to meet the growing need of the population for food on the other hand.

Several means of preservation exist among which drying. This operation can be carried out in two modes: continuous drying and batch drying. In the literature, continuous drying has been applied during the drying of many agro-food products. If the influence of drying parameters on the quality of the product is controlled, it is not the same time and energy consumption during continuous drying. To provide a solution on the energetic level of drying, the researchers turned to discontinuous drying. The most common mode of batch drying is solar drying. Many works have showed the limits of solar drying (not manageable condition) although it is accessible to all and more particularly in the Sahelian zone. The study and the search for ways of optimizing this mode of drying gave birth to intermittent drying.

Intermittent drying is a multi-cycle fractional drying consisting of two phases: a phase of supply of heat to the product and a stop phase (Tetang et al., 2020; Tetang et al., 2014; Chou et al., 2000). This intermittent regime is characterized by its main parameter called "intermittency", whose definition is much diversified. Tetang et al., (2016) and Chua et al., (2003), define the intermittency by the ratio between the “on” period and the cycle period.

This drying technique has already been the subject of several research studies such as those of Mourad et al., 1997 which focused on the intermittent drying of maize in fluidized bed flotation; Chou et al., 2000, on intermittent drying of sweet potatoes; Ben et al., 2010, on the modeling of convective and intermittent drying of carrots, peppers and potatoes; and those of Tetang et al., 2016 and Tetang, 2018, which focused on the intermittent drying of mango samples in a convective dryer.

All of this work focuses on the behavior of the product during drying, however, evaporation is a phenomenon related to the temperature gradient between the product and drying air. It will therefore be a question in this work to characterize the air drying parameters during intermittent drying, in order to show the influence of intermittency on the characteristics of this drying air.

II. MATERIALS AND METHODS

1. Plant Material:

The material used in this work is a mango (Mangifera indica) local variety from the Adamawa Region of Cameroon. The harvest period of this exotic fruit extends from March to July in the year. These mangoes collected, were green and spotted with yellow, when ripe. They have a weight between 150 and 300g.

2. Experimental Device:

It is a forced convection electric modular dryer (fig. 1) capable of operating in two configurations: through flow and licking flow. It is a dryer set up in the Laboratory of Energetic and Applied Thermal of the National School of Agro-Industrial Sciences of Ngaoundere. It has dimensions of 0.52 x 0.72 x 1.80 (m). It is divided into four main parts: the drying chamber, the heating compartment, the blowing system and an air diffuser. It is regulated in temperature using a Pt100 probe.

The thermal operation regulated by the control cabinet is forced convective drying with continuous and discontinuous air. Air enters through the bottom of the dryer before passing through the drying chamber volume that holds up to 10 trays and exits at the top. The air is taken from the environment and then preheated using the heating elements under the action of a turbine. Figure 1 shows the air flow through the drying chamber and the different experimental measuring points. The chips in this figure indicate the positions of the measuring instruments.

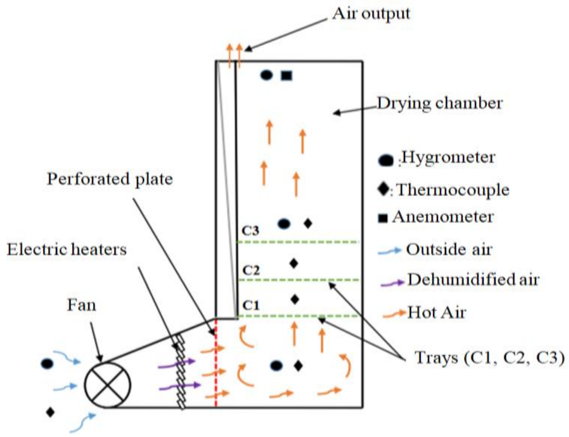

Fig 1. Circulating flow of air through the drying chamber.

3. Measuring Instruments:

The measuring equipment consists of an "Almemo" propeller anemometer FVAD 15S120 R1E4 with a measuring range of 0.01 to 20 m/s to measure the air velocity; three (03) N-type thermocouples (Nikel + chromium) of wide temperature range: -270 to 1300°C for measuring the values of the temperature of the air drying at the outlet of each tray; a SARTORIUS brand digital food scale of type 1264 001; a "Almemo" brand hygrometer ZAD936 RAK, (D6 R5E4) to measure the relative humidity, pressure, and temperature of the air and a data acquisition unit "Almemo 2590" with 4 inputs on which will be mounted two (02) thermocouples, the hygrometer and the anemometer.

4. Methods:

4.1 Samples Preparation:

The mangoes are washed and then rinsed with ordinary water to remove any impurities present on their surfaces. They are peeled, pitted and cut into a thin layer of parallelepiped shape.

During the experimental campaign, the ambient conditions of the local sheltering the dryer are: average temperature 27°C, average relative humidity 50%. The drying chamber can contain ten trays but in the case of this work, only the first three trays will be used.

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The values of intermittency are obtained by equation (1) (Tetang et al., 2016).

$$\alpha = \frac{\tau_{on}}{\tau} = \frac{\tau_{on}}{\tau_{on} + \tau_{off}} \qquad \textbf{(1)}$$

Where;

α : Intermittency (-)
τ : cycle period (minutes)
τ_{off} : "off" period (minutes)
τ_{on} : "on" period (minutes)

4.2 Drying Process:

The experimental conditions of the various tests are given in Table 1.

Table 1. Experimental conditions of intermittent drying.

Parameters	Values
Air drying temperatures (°C)	40 ; 50 ; 60
velocity (m/s)	1.37
Intermittency (α)	¼ ; ½ ; ¾
τ_{on} (min)	30 ; 60 ; 90
τ_{off} (min)	90 ; 60 ; 30
τ (min)	120
Mass of samples (g)	500 ; 800

For each test, the characteristics of the drying air (relative humidity, temperature, air pressure and velocity) at the inlet and outlet of the drying chamber shall be determined.

For the three trays used, it will be necessary on the one hand to determine the temperature and the relative humidity of the air drying at the exit of a tray and the pressure of the drying chamber, and other to characterize the influence of the intermittency and the presence of the products on the air flow inside the drying chamber.

For this, the thermocouples are placed at the exit of each tray to take the temperature of the drying air, and the hygrometer placed at the exit of the drying chamber to obtain the degree of hygrometry of the air drying out for each of the experiments performed.

The experimental protocol leading to obtaining the values of the different parameters of the drying air is that described by Tetang et al., 2016, which has been completed (Fig. 2).

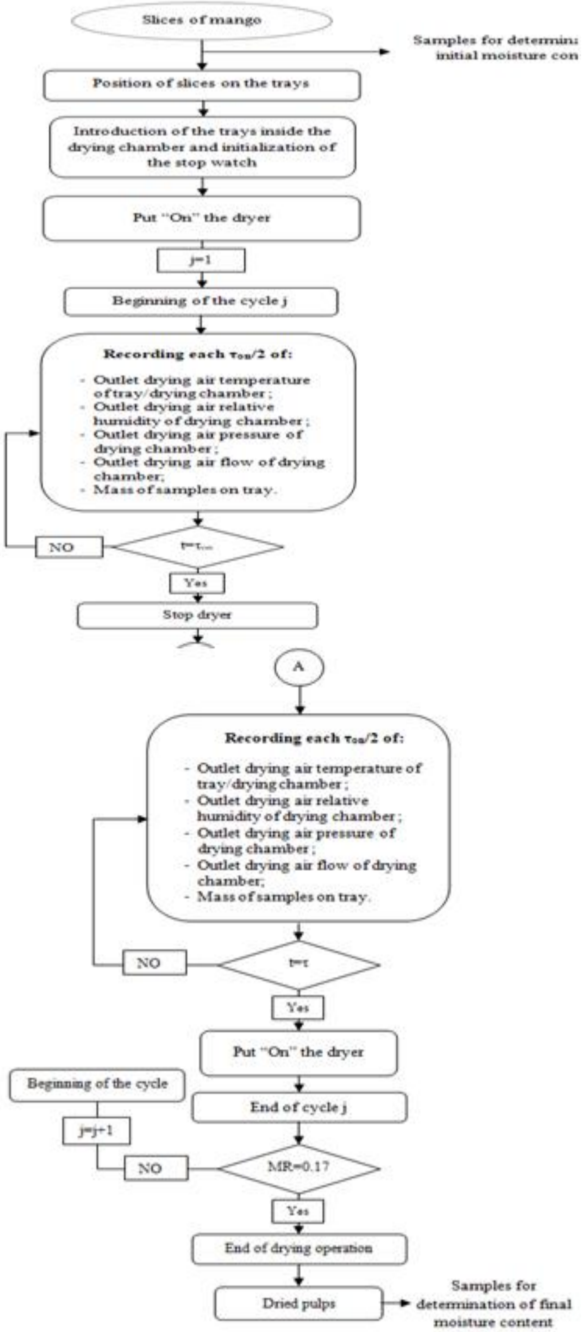

Fig 2. Experimental procedure (Tetang et al., 2016 completed).

III. RESULTS AND DISCUSSION

1. Characterization of the Air Flow in the Empty Drying Chamber:

1.1

Influence of Intermittency on the Profile of the Drying Air Relative Humidity: Figure 3 shows the evolution of the temperature and the relative humidity of drying air in the empty drying chamber for the intermittency α equal to ¼, and the air drying inlet temperature of 40°C.

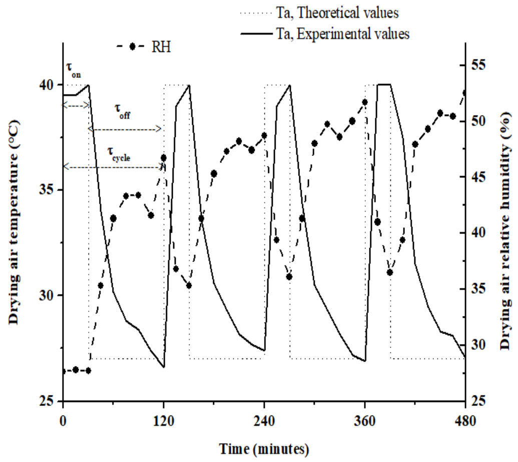

Fig 3. Profiles of the drying air temperature and relative humidity in the drying chamber (T_a = 40°C and α = ¼).

Figure 3 shows that the drying air relative humidity increases during the "off" period (non supply of heat to the air), and goes progressively according to the number of cycles, until reaching the value the relative humidity of the local ambient air. This is explained by the fact that the ambient air (T = 27°C) enters the drying chamber in natural convection.

On the other hand, it decreases during the operation of the dryer at 40°C (supply of heat to drying air). This phenomenon is repeated almost every cycle that lasts 120 minutes. This result is in agreement with the literature which shows that the evolution of the relative humidity of the air is inversely proportional to the evolution of the temperature. This result is also obtained at 50 and 60°C for this same value of the intermittency.

In addition, there is a discrepancy between the experimental and theoretical curves. This offset is due to the thermal inertia inside the drying chamber, and this is related to the volume of the latter and the air velocity. It can therefore be seen that the drying air temperature during the "off" periods falls slightly, because it is natural convection. But as soon as the dryer is put back into operation, this temperature rises quickly because of the forced convection imposed by the fan. And also, the downtime being longer than the supply time in hot air, it is noted that at the beginning of each recovery, the drying chamber is fully at room temperature.

In Figure 4, there is a very sharp decrease in the air relative humidity from 50 to 29% during the first 60 minutes during operation of the dryer at 50°C.

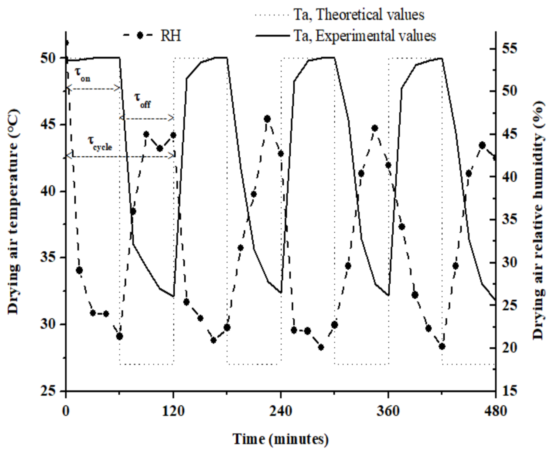

Fig 4. Profiles of the drying air temperature and relative humidity in the drying chamber (T_a = 50°C and α = ½).

However, during the "off" period, it increases until reaching the value of 44% which is lower than that of the outside air, compared with fig 3. This observation is justified by the fact that the "off" period is shorter than that of α = ¼. This phenomenon is repeated at each cycle during the 8 hours of the test. It can therefore be said that the increase in the intermittency α and the drying air temperature causes an increase in the air evaporative power.

Regarding the evolution of the experimental temperature, unlike the intermittency α=¼, it is noted that the drying chamber is each time at a temperature higher than that of the ambient air. This is due, on the one hand, to the fact that the "off period" is smaller and, on the other hand, to the fact that the drying air temperature is higher in this case.

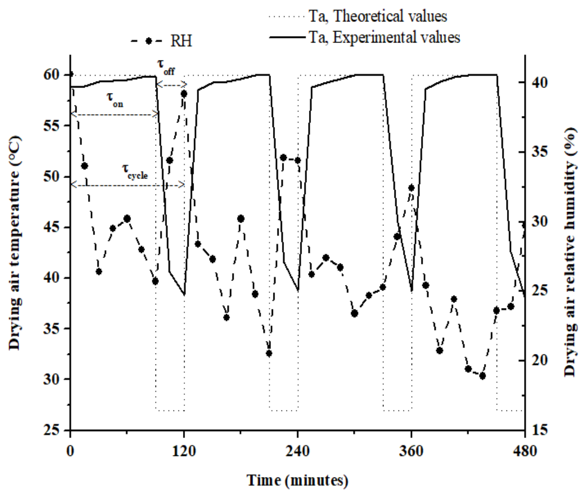

Fig 5. Profiles of the drying air temperature and relative humidity in the drying chamber (T_a = 60°C and α = ¾).

The observation of the fig. 5 shows a very strong decrease of the air humidity inside the drying chamber as a function of time for α = ¾. This reflects the increase in the air water absorption capacity.

This result is consistent with those of the literature which shows that the air humidity reduces with the increase of the temperature in the time. It is also noted that the higher the number of cycles, the lower the air relative humidity inside the drying chamber.

With regard to the temperature curves of this figure also, there is always a shift between the theoretical and experimental curve, which shift in the case is as significant as in the two previous cases. As the number of drying cycles increases, it is noted that the experimental temperature tends to stabilize at 60°C, the drying air temperature at the entrance in the drying chamber.

This phenomenon can be justified by the fact that the drying air humidity inside the chamber continues to decrease, which imposes a rapid rise in temperature.

1.2 Influence of Intermittency on the Evolution of the Drying Air Temperature:

Figure 6 gives the profile of the air temperature at 40°C in the drying chamber for α=½ at the outlet of each of the three trays during empty tests.

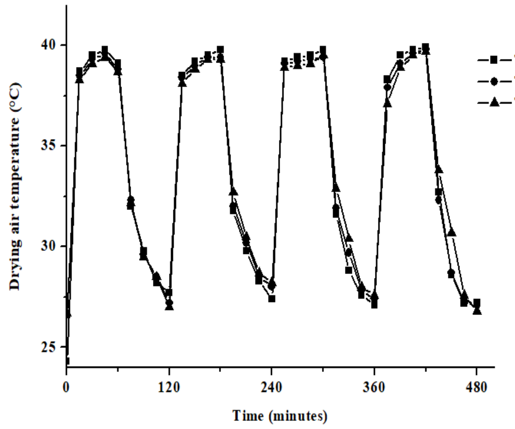

Fig 6. Profiles of the drying air temperature at the outlet of the different empty trays in the drying chamber (T_a = 40°C and α = ½).

Figure 6 shows that whatever the position of the tray, the evolution of the temperature profiles is consistent. There is also a near-instantaneous rise in air temperature after the heat source (120, 240, 360 and 480 minutes) has been restarted.

These results reflect the uniformity of the temperature inside the drying chamber. These same observations were made in the literature by Kuitche et al., 2006, during the vacuum test with trays on the evolution of the temperature inside the drying chamber as a function of the distance with respect to the heat source.

1.3 Influence of intermittency on drying air pressure:

Figure 7 shows the profile of the air pressure in the vacuum drying chamber for the three different values of α.

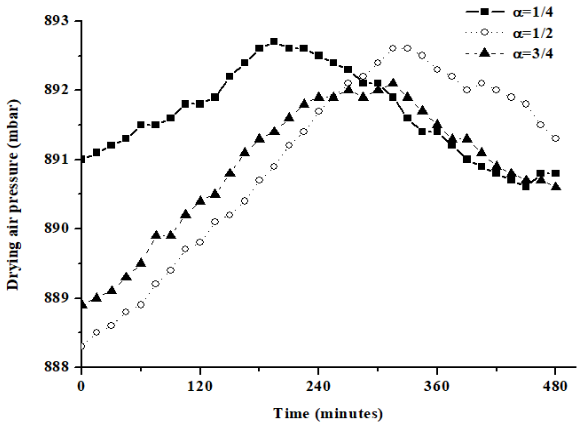

Fig 7. Evolution of the drying air pressure in the empty drying chamber for the three values of α at T_a = 40°C.

In general, the fig. 7 shows that the three pressures evolve between the values 888 and 893 mbar. These curves have a compression phase of 180; 240 and 300 minutes, respectively for α equal to ¼; ½ and ¾. This generates a longer relaxation phase for α = ¼. The three curves are almost identical and have the same pace at 40°C.

The comparison of this result with those of 50 and 60°C, showed that during the "off" or "on" period, the variation of the drying air pressure is not considerable. It can then be concluded that the intermittency has no influence on the drying air pressure inside the empty drying chamber.

1.4 Profiles of drying air velocity at the entrance of the empty drying chamber:

Figure 8 shows the profiles of the drying air velocity at the entrance of the drying chamber for the three values of intermittency α (¼ ½ and ¾) at 40; 50 and 60°C.

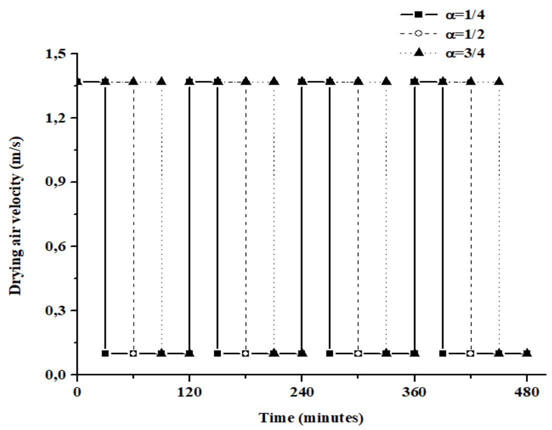

Fig 8. Profiles of drying air velocity at the entrance of the drying chamber.

This figure shows that the drying air velocity oscillates between the values 1.37 m/s and 0.1 m/s, which correspond respectively to the "on" periods (forced convection) and "off" periods (natural convection).

The different profiles have the same amplitude and differ only with the phase which is the intermittency. It can be concluded that the intermittency has no influence on the drying air velocity at the entrance of the drying chamber.

2. Characterization of the Air Flow in the Drying Chamber Under Load:

2.1 Influence of Drying Air Temperature:

2.1.1 On its relative humidity: For α = ½, Fig. 9 shows a saw tooth profile.

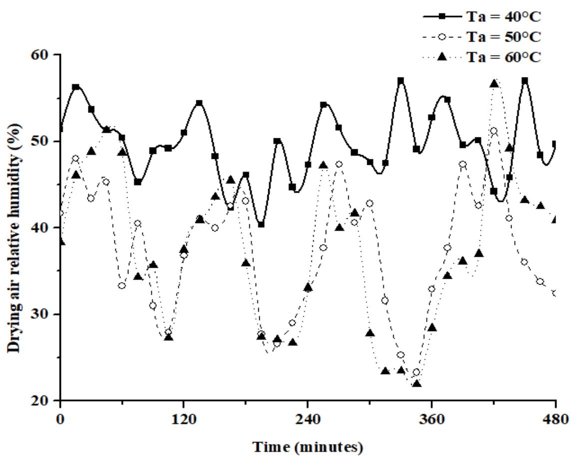

Fig 9. Profiles of the relative humidity of the air drying at the exit of the drying chamber for α =½.

It is observed that throughout the duration of the operation of the dryer under load, the drying air relative humidity at 40°C varies between 42 and 56%. On the other hand, at 50 and 60°C, it goes down to 23.3 and 21.9% respectively. The analysis of the results shows that at high temperature, the relative humidity of the air is low. The curves in fig. 9 show that the air humidity is variable in space and time. It is mainly influenced by the amount of water available and the temperature.

This result shows that the temperature of the drying air has a considerable influence on the variation of its relative humidity.

2.1.2 On his pressure: Figure 10 shows the profiles of the air pressure at the outlet of the drying chamber.

The analysis of the curves shows that after 480 minutes, the different variations of the pressure are 3; 4 and 4.5 mbar respectively at 40; 50 and 60°C. Whatever the temperature, we note that the drying air pressure is increasing for 420 minutes.

From this same time, we observe a convergence of all the pressure curves (ΔP ≤ 1 mbar) until the end of drying. At a temperature of 60°C, a greater increase of the air pressure from the beginning to the end of the drying compared with the air pressure curves at 40 and 50°C is achieved.

This observation was also made for the evolution of the air pressure at the inlet of the empty drying chamber for α = ¼ and ½. It is observed that the variation of the air pressure is not significant. However, it is understood that the increase in temperature causes an increase in air pressure.

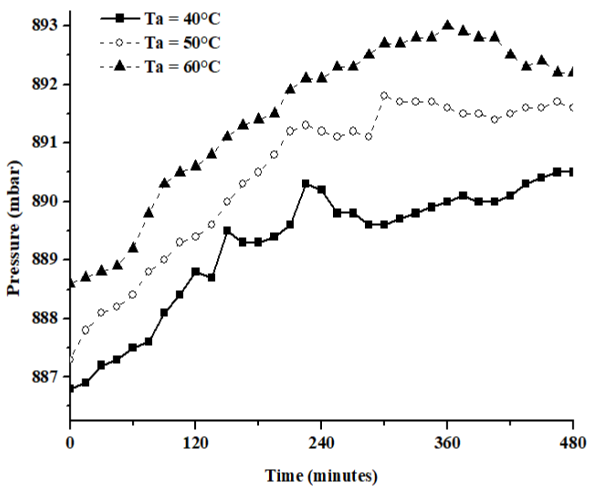

Fig 10. Evolution of the air pressure drying at the outlet of the drying chamber for α = ½.

2.2 Influence of the load on the parameters of drying air during drying:

2.2.1 Relative humidity: Figure 11 shows the evolution of the air relative humidity as a function of time at the outlet of the drying chamber.

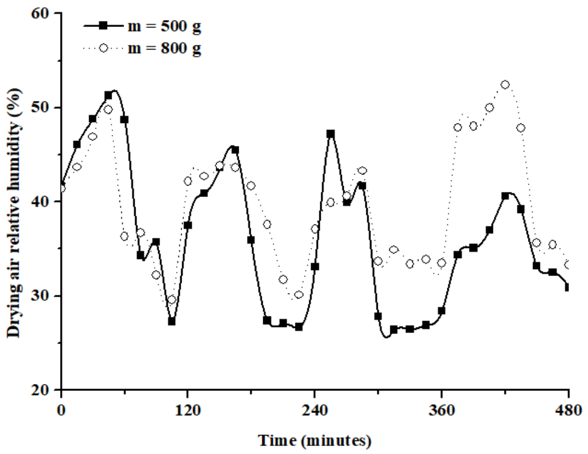

Fig 11. Evolution of the relative humidity of the air at the outlet of the drying chamber at 60 ° C and α = ½

During the first cycle, the drying air relative humidity is 51.3 and 49.8% respectively for 500 and 800g. But in the last cycle, the phenomenon is reversed; it is then 40.6 and 52.4% respectively at 500 and 800g.

For 500g/tray, the air relative humidity decreases more rapidly. This is because the air absorbs less water into the product during this time. On the other hand for 800g, the absorption in water is more important in the last cycle.

2.2.2 On the pressure: Figure 12 shows the profiles of the air pressure at the outlet of the drying chamber.

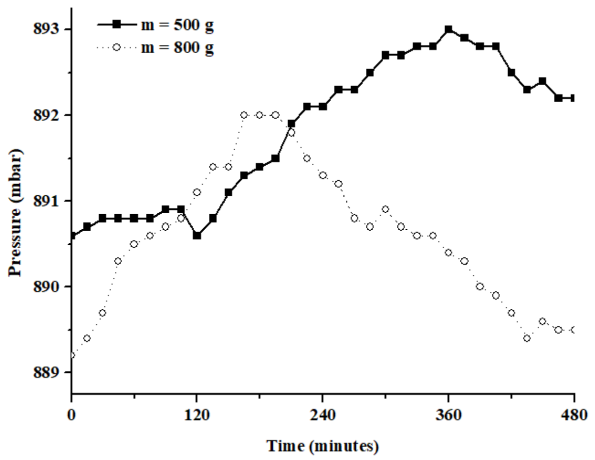

Fig 12. Evolution of the air pressure at the outlet of the drying chamber at T_a = 60°C and α = ½.

The curves of fig. 12 show the same start pace up to 200 minutes, at which time a gap appears between the two curves until the end of the operation.

From 200 minutes, the air pressure for 800g decreases until 420 minutes then remains almost constant until the end of drying. For the mass of 500g, it's the opposite phenomenon.

2.2.3 On the temperature:

- **Out of the first tray:** Figure 13 shows the evolution of the temperature of the air at the outlet of the first tray at 60°C. It reveals an increase of the ambient temperature to the set temperature during operation and the decrease of this temperature during the "off" period.

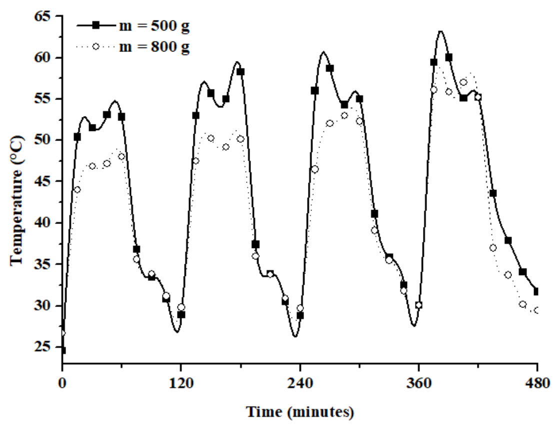

Fig 13. Profiles of the air temperature at the outlet of the first tray at α = ½ at 60°C.

The analysis of the curves shows a progressive increase of the temperature at the exit of the first tray. It is more important for the case 500g/tray, which is an advantage because it allows a good evaporation of water product; hence the reduction of the drying time.

On the other hand, for 800 g, the outlet temperature of the first tray is around 50°C. after 300 minutes during the operation of the dryer at 60°C.

- **At the exit of the drying chamber:** The outlet temperature of the drying chamber for 500g mango samples is higher than that of 800g. It reaches up to a temperature of 52.5°C at the outlet of the drying chamber for 500g case during the 480 minutes. On the other hand, with 800 g after this same time at the same drying temperature, it reaches about 50°C (Fig. 14).

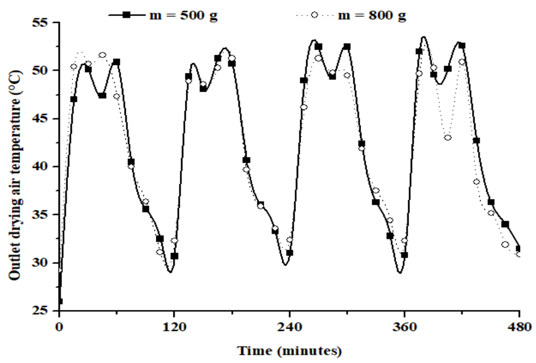

Fig 14. Profiles of the outlet drying air temperature of the drying chamber (T_a = 60°C; α=½)

2.2.4 On the flow regime: In Figure 15, during the first 20 minutes, the air flow intensifies (Re > 45000): the air velocity at the outlet of the drying chamber increases. 20 minutes later, this regime drops hence the decrease in the number of Reynolds up to 35000 and 45000 respectively for the masses 500 and 800g. This phenomenon is repeated at each cycle, which lasted 120 minutes. For 800 g, a very high flow rate is reached at the outlet of the drying chamber compared to that of 500 g.

Figure 15 shows that the flow regime during the different operating periods of the dryer is turbulent because Re > 5000.

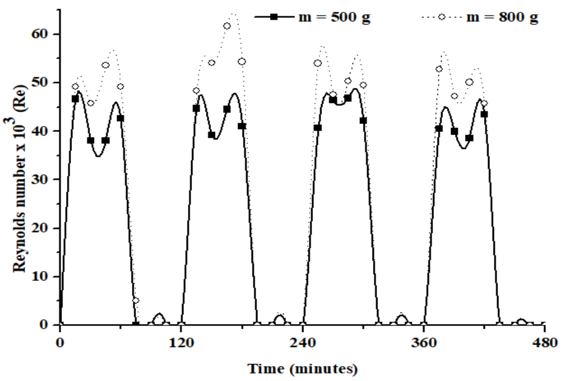

Fig. 15. Profile of the air flow at the outlet of the drying chamber for initial masses of 500 g and 800 g of mango/tray at α = ½

2.3 Influence of intermittency on the parameters of drying air at the exit of the drying chamber:

2.3.1 Relative humidity: Figure 16 shows that during the first cycle, the three curves have a similar behavior, and are very close for a drying time of 30 minutes. But 6 hours later, that is to say 390 minutes, they are all distant from each other. Then the relative humidity of the air at this moment is 51.9; 47.3 and 36.7% respectively for α = ¼; ½ and ¾.

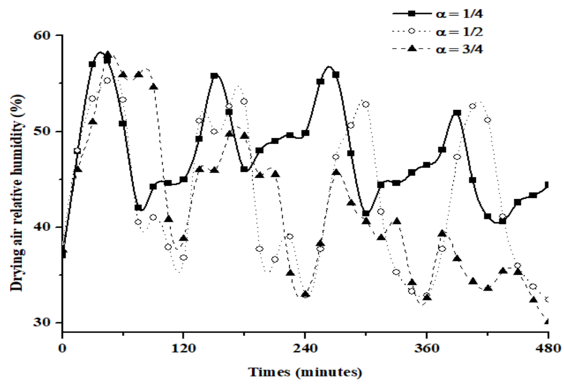

Fig 16. Profiles of the drying air relative humidity at the outlet of the drying chamber at 50°C for 500g of product/tray.

Analysis of the curves shows that for α = ¾ and at 390 minutes, the air relative humidity at the outlet of the drying chamber is substantially equal to that of the inlet. This can be explained by the fact that the quantity of water contained in the product is almost absorbed; which leads to a significant reduction in water loss. Also, in general, for α = ¾, the air absorbs more water into the product.

On the other hand, the air absorbs less water in the product at α=¼ and ½ during the operation of the dryer at 50°C. These results are in agreement with those of Tetang et al., 2015, and Tetang, 2018, which show that for α = ¾, the drying time is shorter.

2.3.2 On the pressure: Figure 17 shows an increase in air pressure from the beginning to the end of drying for α = ½ and ¾ at 50°C. On the other hand, for α = ¼ the air pressure decreases during the first 180 minutes, then is almost observed until 300 minutes before increasing until the end of the drying operation.

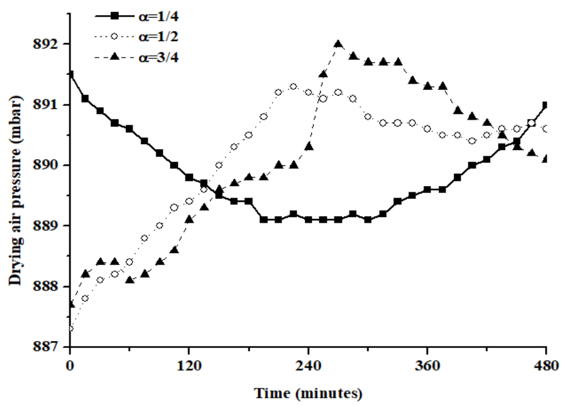

Fig 17. Evolution of the air pressure drying at the outlet of the drying chamber at 50°C for 500g of product/tray.

2.3.3 On the temperature: Figure 18 shows the evolution of the air temperature at the outlet of the drying chamber for α = ¼, ½ and ¾ at the drying temperature of 50°C for 500g of mango samples per tray. In this figure appears a first increasing phase, which corresponds to the heating of the air in the drying chamber. For α = ¾, the outlet temperature of the drying chamber increases to 46°C during the first 90 minutes of the drier's operating time before decreasing to reach the outside air temperature.

This is explained by a good heat exchange between the air and the product during the drying process. The highest temperatures obtained for α = ¼ and ½ are respectively 42 and 44°C for respective drying times of 380 minutes and 150 minutes.

The results of these analyses show that intermittence α = ¾ allows the evaporation of a large quantity of water contained in the product. These results are in agreement with those of Tetang et al., 2015 and Tetang, 2018.

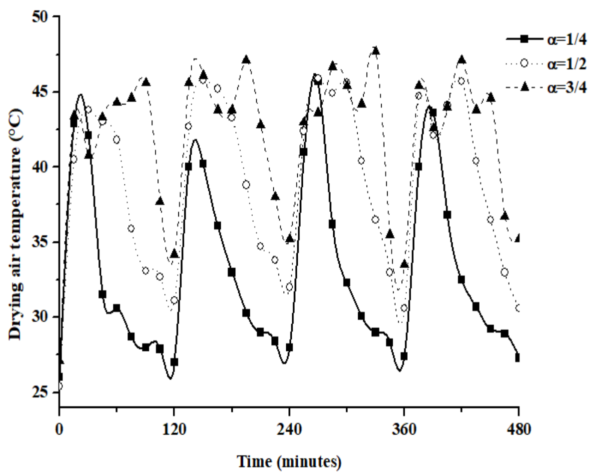

Fig 18. Evolution of the drying air temperature at the outlet of the drying chamber at 50°C.

2.3.4 On the air flow: Figure 19 shows that the first 15 minutes corresponds to the setting of the flow of air at the outlet of the chamber independently of the value. This phenomenon is repeated at each cycle.

The analysis of these curves shows that for α = ¼, a Reynolds number of 75000 is reached during the 30 minutes of operation of the dryer at 50°C.

On the other hand, at the same time, it is 64000 and 61000 respectively for α = ½ and ¾. It is therefore a turbulent flow regime observed in the drying chamber during the operation of the dryer.

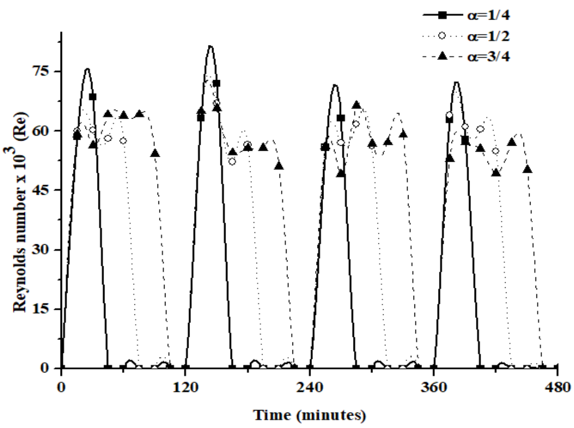

Fig 19. Profiles of the air flow at the outlet of the drying chamber at 50°C.

IV. CONCLUSION

Continuous drying involves the excessive consumption of energy by the dryer. In order to provide solutions to this problem, several techniques have been developed among which intermittent drying to solve this problem. In the west tropical zone, where air hygrometry and rainfall are very high, the characterization of the airflow remains very important. In order to make a contribution, this study has been concerned with a study of the regime of the drying air flow in the drying chamber during intermittent drying.

Tests carried out in a modular forced convection dryer revealed the influence of intermittency on the pressure, the different temperatures, the flow regime and the relative humidity of the air drying during the drying operation. The analysis of the results shows, on the one hand, that during the vacuum tests, for 53% relative humidity of the outside air, the passage through a heating resistor of 2442 W, led after respectively 270; 240 and 210 minutes, 37.5; 20 and 19% relative humidity for respective temperatures of 40; 50 and 60 ° C, and for respective values of α = ¼, ½ and ¾. And also, the presence of vacuum trays in the drying chamber had almost no influence on the temperature of the air in this chamber.

On the other hand, during the load tests, the analysis of the results obtained showed that the drying air relative humidity at the outlet of the drying chamber is greater at equal temperature for α = ¾, and that the flow regime of the air in the drying chamber was turbulent. Also, the mass of the samples on the trays has a significant influence on the evaporative power of drying air.

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