Characterization of the Drying Kinetics of Pineapple Slices and Improvement of a Drying Process in Uganda

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ABSTRACT

This master thesis was accomplished in partnership with the non-governmental organisation The Refugee Next Door© (RND©). In the first part of it, a better understanding and a modelling of the pineapple slice drying operation are presented. The analysis of the drying kinetics of pineapple slice was performed under different operating conditions. The slices of 4, 6 and 8 mm were dried at 65°C using different air flow rates of 8, 13, 17 and 18 Nm^3/h in a laboratory scale tunnel dryer. The influence of the air velocity and slice thickness on the drying kinetics was investigated in order to discuss the importance of the internal and external mass transfer during the drying operation. The results have shown that the internal and external heat and mass transfer must be considered at the beginning of the drying operation. After a certain period of time, the internal diffusion becomes predominant over the external mass transfer. Based on a mathematical model and on the experimental data, the effective diffusion coefficients could be calculated. They vary from $2.34\ 10^{-10}$ to $5.57\ 10^{-10}$ m^2/s. In the second part of this master thesis, the improvements implemented in Uganda to make the drying process more efficient are presented. The construction of the new processing centre and the ventilated solar tunnel dryers was supervised. Practical improvements were implemented to increase the lifetime of the ventilated solar tunnel dryer. Finally, in the last part of this work, the results regarding the performed experiments on the ventilated solar tunnel dryer are presented in order to validate the design conditions which ensure an efficient drying operation. The relative humidity within the dryer remained far below 100% during the drying operation and the relative humidity remained below 100% during the night which prevented the condensation to take place during the performed experiments. The average temperatures within the dryer were lower than the calculated theoretical ones. However, the temperatures during the drying operation reached adequately high temperatures during a sufficiently long period of time to consider the drying operation as efficient. An attempt to estimate the efficiency of the ventilated solar tunnel dryer was achieved. The calculated efficiency is 9% on average.

Keywords: Ventilated solar tunnel dryer, pineapple slice, drying kinetics, mathematical modelling, drying process, Uganda.

Onderzoek naar de droogkinetiek van ananasschijven en optimaliseren van een droogproces in Uganda

ABSTRACT

Deze Master thesis is gemaakt in samenwerking met de niet-gouvernementele organisatie Refugee Next Door® (RND®). Deel één bespreekt het drogen en het modelleren van het drogen van de ananasschijven. De analyse van de droogkinetiek van de ananasschijven was uitgevoerd onder verschillende omstandigheden. Ananasschijven van 4, 6 and 8 mm waren gedroogd in een tunneldroger op labschaal op 65°C met het gebruik van verschillende luchtdebieten: 8, 13, 17 en 18 Nm^3/h. De invloed van de luchtsnelheid en schijfdikte op de droogkinetiek is onderzocht om het belang van interne en externe diffusie tijdens het proces te bespreken. De resultaten toonden aan dat de interne en externe warmte- en massatransport in rekening moet worden genomen tijdens het begin van het proces terwijl de interne diffusie de overhand neemt tijdens de rest van het droogproces. Met behulp van een wiskundig model en experimentele data kunnen effectieve diffusiecoëfficienten worden berekend. Deze varieerden van $2.34\ 10^{-10}$ tot $5.57\ 10^{-10}$ m^2/s. In het tweede deel van de thesis zijn de verbeteringen aangebracht aan het droogproces in Uganda voorgesteld. De bouw van het nieuwe verwerkingscentrum en de geventileerde zonnetunneldrogers is opgevolgd. Praktisch voorgestelde verbeteringen werden aangebracht om de levensduur van de drogers te verlengen. Het laatste deel van dit thesis bestudeert de werkomstandigheden van de zonnetunnels om zo een optimale droging te bekomen. De relatieve vochtigheid binnen de drogers bleef ver beneden 100% tijdens het droogproces en bleef eveneens beneden 100% tijdens de nacht zodat condensatie werd vermeden. De gemiddelde temperatuur binnen de droger was lager dan de vooropgestelde temperatuur. Echter, de temperatuur tijdens het drogen was voldoende hoog voor een voldoende lange periode om toch het drogen als efficiënt te beschouwen. De gemiddelde efficiëntie van de zonnetunneldroger is geschat op 9%.

Sleutelwoorden: geventileerde zonnetunneldrogers, ananasschijf, wiskundige modellen, droogprocess, Uganda.

Caractérisation de la cinétique de séchage de tranches d'ananas et amélioration d'un procédé de séchage en Ouganda

ABSTRACT

Ce mémoire a été réalisé en partenariat avec l'organisation non gouvernementale The Refugee Next Door© (RND©). Tout d'abord, une analyse ainsi qu'un modèle du séchage d'ananas sont présentés dans la première partie ce mémoire. Différentes conditions expérimentales ont été utilisées pour analyser la cinétique de séchage des tranches d'ananas. Des tranches d'une épaisseur de 4, 6 et 8 mm ont été séchées à 65°C en utilisant des débits d'air de 8, 13, 17 et 18 Nm^3/h. Ces expériences ont été réalisées dans un séchoir tunnel en laboratoire. L'influence de la vitesse de l'air et de l'épaisseur des tranches sur la cinétique de séchage des ananas a été étudiée pour discuter de l'importance des transports de matière interne et externe durant l'opération de séchage. Les résultats de ces expériences ont montré que les transferts de chaleur et de matière à l'intérieur ainsi qu'à la surface de la tranche d'ananas avec l'air doivent être considérés au début du séchage. Après un certain temps, les transferts internes deviennent prédominants et les transports externes peuvent être négligés pour décrire la cinétique de séchage. Basé sur les résultats expérimentaux et un modèle mathématique, des coefficients effectifs de diffusion ont pu être calculés. Ces coefficients ont des valeurs qui varient entre $2.34\ 10^{-10}$ et $5.57\ 10^{-10} \mathrm{m}^2/\mathrm{s}$. La seconde partie de ce mémoire présente les améliorations mises en place en place en Ouganda pour rendre le procédé de séchage plus efficace. La construction d'un nouveau centre de production ainsi que celle de séchoirs tunnels solaires ventilés ont été supervisées. Des améliorations pratiques ont été mises en place afin d'assurer une plus longue durée de vie des séchoirs. Dans la dernière partie de ce mémoire, les résultats des expériences effectuées sur le séchoir tunnel solaire en Ouganda sont présentés. Ces résultats sont discutés afin de valider les conditions de fonctionnement qui garantissent un séchage efficace. L'humidité relative de l'air au sein du séchoir restait bien en dessous de 100% durant l'opération de séchage et celle-ci était inférieure à 100% durant la nuit. Cette observation permet de dire que la condensation n'a pas pris place au sein du séchoir lors des expériences réalisées. Les températures qui ont été atteintes dans le séchoir sont restées inférieures à celles calculées théoriquement. Cependant, la température au sein du séchoir a atteint des valeurs suffisamment élevées pendant une période assez longue pour assumer que les conditions d'un séchage efficace ont été remplies. Une estimation du rendement du séchoir solaire a été calculée et celle-ci est en moyenne de 9%.

Mots-clés : séchoir tunnel solaire ventilé, tranche d'ananas, cinétique de séchage, modèle mathématique, procédé de séchage, Ouganda.

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Symbol	Definition	Units
A_{air}	Expected airflow	kg air/s
$A_{nom,air}$	Nominal air flow velocity	m^3/s
$c_{p,a}$	Heat capacity of air	J/(kg K)
C_0	Initial water concentration	kg water/m^3 pineapple slice
C_{eq}	Equilibrium concentration at the inner surface of the pineapple with air interface	kg water/m^3 pineapple slice
$C(z,t)$	Concentration of water in position z for time t	kg water/m^3 pineapple slice
$<\widetilde{C}>(t)$	Average concentration of water depending only on time	kg water/m^3 pineapple slice
$\mathbf{d.b}$	Dry basis	
$\mathcal{D}_{eff}$	Effective diffusion coefficient	m^2/s
$\mathcal{D}_{eff,ref}$	Effective diffusion coefficient chosen as a reference	m^2/s
D_h	Hydraulic diameter of the transversal cut to the flow	m
E_u	Useful energy. The energy consumed to heat up the air and to evaporate water	MJ
E_{solar}	Solar energy captured by the solar tunnel dryer	MJ
e_p	Plastic foil thickness	m
e	thickness	m
F_s	Direct and diffuse solar radiation flux	W/m^2
$F_{IR,in}$	Infrared energy flux between the black floor and the inner surface of the plastic foil	W/m^2
$F_{IR,atm}$	Atmospheric infrared radiation flux	W/m^2
$F_{conv,in}$	Convective heat transfer between the black floor and the air within the dryer	W/m^2
$F_{conv,p}$	Convective heat transfer between the inner surface of the plastic foil and the air within the dryer	W/m^2
$F_{cond,p}$	Conduction heat transfer through the thickness of the plastic foil	W/m^2
$F_{conv,out}$	Convective heat transfer between the outer part of the plastic foil and the ambient air	W/m^2
F_{evap}	Evaporation flux of water from the products	W/m^2
$F_{IR,out}$	Infrared energy flux from the outer surface of the plastic foil and the ambient air	W/m^2

$\mathbf{g}$	Standard acceleration due to gravity	m/s²
Gr	Grashof number	
H	Thickness of the pineapple slice	m
$h_{p,i}$	Convective heat transfer coefficient of the inner surface of the plastic foil	W/(m²K)
$h_{p,o}$	Convective heat transfer coefficient of the outer surface of the plastic foil	W/(m²K)
h_{fl}	Convective heat transfer coefficient of the floor	W/(m²K)
h	Convective heat transfer coefficient	W/(m²K)
J	Drying rate (dry basis)	kg water evaporated/(kg dry matter and s)
k_p	Thermal conductivity of the plastic foil	W/(m K)
k	Thermal conductivity	W/(m K)
k_a	Thermal conductivity of air	W/(m K)
$\mathcal{L}_w$	Mass latent heat of vaporisation of water	J/kg
L_D	Length of the drying part	m
m_{fresh}	Fresh products mass	kg
M_a	Molar mass of the air	g/mol
M_w	Molar mass of water	g/mol
$M(t)$	Mass of pineapple slice continuously measured	kg
m_f	Final dried mass after 24h at 70°C in the oven	kg dry matter
m_i	Initial mass introduced in the oven	kg
m_w	Water mass	kg water
M_d	Dried mass of pineapple slice in the dryer	kg dry matter
M_0	Initial mass of pineapple slice in the dryer	kg
$m_{water,evap}$	Mass of water evaporated	kg water
M_s	Mass of fresh products expressed by surface area	kg/m²
M_f	Mass obtained at the end of the drying experiment in the tunnel dryer	kg
Nu	Nusselt number	
P	Energy flux transmitted to the air within the dryer by the floor and the inner surface of the plastic foil	W/m²
Pr	Prandtl number	
p_w	Partial pressure of water in air	Pa
p_{tot}	Total pressure of air	Pa
$p_{sat}(T)$	Saturation pressure of water at temperature T	Pa
q_{rad}	Radiation heat transfer	W/m²
q_{cond}	Conduction heat transfer	W/m²
q_{conv}	Convection heat transfer	W/m²
Q_{evap}	Heat quantity required to water evaporation	W

RH_{dry}	Relative humidity of the air at the end of the drying zone	%
RH_{heat}	Relative humidity of the air at the end of the heating zone	%
RH_{amb}	Relative humidity of the ambient air	%
R	The aspect ratio between the area of the plastic foil and the width of the dryer	
Ra	Rayleigh number	
T	Absolute temperature	K
T_{fl}	Black floor of the dryer temperature	K
T_{amb}	Ambient temperature	K
$T_{p,i}$	Inner surface temperature of the plastic foil	K
$T_{p,o}$	Outer surface temperature of the plastic foil	K
T_{air}	Air temperature within the dryer	K
T_{sky}	Sky temperature	K
T_{dp}	Dew point temperature	°C
T_w	Wall temperature	K
T_∞	Fluid stream temperature	K
T_{ini}	Temperature on one side of the medium	K
T_{end}	Temperature on the other side of the medium	K
$T_{air,heat}$	Temperature of the air at the end of the heating zone	K
$T_{air,dry}$	Temperature of the air at the end of the drying zone	K
t_c	Characteristic drying time	s
t_d	Drying time	s
W_D	Width of the drying part	m
X_0	Initial moisture content (dry basis)	kg water/kg dry matter
X_f	Final moisture content (dry basis)	kg water/kg dry matter
$X(t)$	Moisture content (dry basis)	kg water/kg dry matter
Y	Absolute humidity of the air	kg of water/kg of dry air
β_a	Thermal expansion coefficient of air	K^{-1}
ε_{sky}	Emissivity of the sky	[0,1]
ε	Emissivity	[0,1]
η_{std}	Efficiency of the solar tunnel dryer	%
ν_a	Kinematic viscosity of air	m^2/s
ξ	Ground surface of the solar tunnel dryer	m^2
ρ_a	Air density	kg/m^3
σ	Stefan-Boltzmann constant	$W/(m^2\ K^4)$
Ω	Surface of the pineapple slice	m^2

CHAPTER 1: INTRODUCTION

1.1 Situation

1.1.1 Uganda overview

Uganda is a landlocked country in East Africa located to the east of the Democratic Republic of the Congo (DRC). It is bordered by South Sudan, Kenya, Tanzania, Rwanda and the DRC [1]. The geographic location of Uganda among Africa is shown in Figure 1. The area of the country is 241,548 km² and the Ugandan population counts 37,101,745 inhabitants with an annual population growth rate of 3.24% which is one of the highest in the world (2015) [2,3]. Only 55.6% of the teenagers complete the 7 years of primary school. In 2012, it was estimated that 19.5% of the population lived under the national poverty lines [4]. Around 20 millions of inhabitants live in rural areas [5].

Figure 1: Geographic location of Uganda within Africa and detailed map of Uganda [1]

Since 1986, the government with the help of foreign countries has put in place political measures in order to rehabilitate and stabilize the economy. It undertook the promotion of the exportation by raising the producer prices and it increased the salary of the public administration while it has increased also the prices of petroleum products. These measures were undertaken to ensure a continuous and sustainable economical growth based on investment. Despite the economic downturn in 2008, Uganda's Gross Domestic Product (GDP) seemed to resist to the decrease in exportation demand thanks to the previous reforms. However, corruption and insufficient transport network investment lead to inhibit economic development and investor confidence [3].

On the other hand, Uganda owns considerable natural resources such as small deposits of noble metals, minerals and fertile soils. Recently, they also discovered oil [3]. Nevertheless, the agriculture sector remains the most important sector among others because it employs around 82% of the available labour force [3,6]. Agriculture represents 26.3% of the Uganda's GDP and 85% of total export earnings [4,5,6]. Uganda's GDP is around 27 billion US$ [4].

1.1.2 Fruits agriculture in Uganda

As previously mentioned, the primary sector, where agriculture plays a fundamental role, is responsible for the performance of the Ugandan economy. This is the reason why the agricultural sector was considered as a pillar of the National development plan and became an integral part of the investment plan's priority [7]. The objectives of the agricultural sector are numerous; they promote employment by introducing internal and external trade and they also improve quality of life of small households by increasing their incomes. These objectives aim at promoting a sustainable economic growth. They also struggle against malnutrition and hunger. The objectives of the agricultural sector improve nutrition security when it is known that fewer than 15% of the population are estimated undernourished [7,8,9].

More precisely, the natural conditions which are encountered in Uganda promote agriculture. The climate is tropical with two dry seasons (December to February, June to August) and two rainy seasons while it is semiarid in the northeast. These two seasons can lead to two different harvests within the year for particular crops, such as pineapples for example. In terms of competitiveness, this is a considerable advantage compared to other countries [2,10]. Ugandan agriculture can remain competitive thanks to its fertile soils. A lot of different horticultural crops can grow without chemical products. Ugandan agriculture owns an important available labour force to maintain the crops in a good state without weeds [7,11].

Ugandan people use to practice subsistence agriculture as they own small land fields and they grow intercropped vegetables and fruits. Recently, more and more farmers started transforming their subsistence farming to commercialized agriculture thanks to the National development plan. Thus, fruit farming has increased during the last decade as it provides them a sustainable business in comparison to vegetables. It offers a better income than other crops and the fruits are easier to sell as they can be sold either in the internal market or in the export market. As an example: a lot of Ugandan people prefer to cultivate pineapples instead of coffee because they are more resistant against pest and diseases. In addition, it is more profitable to plant pineapples than coffee in a small field even if a more important maintenance work is required [7,12,13].

However, strong competitors of exotic fruits exportation are present in Africa such as Côte d'Ivoire, Kenya and Ghana. Ugandan fruits and vegetables exportation is low as it can be seen in Table 1 although the harvest occurs between November and February when the fresh fruits demand is high in European countries [11]. This can be explained by the location of Uganda which is a landlocked country. Hence, the transportation costs are expensive and the transportation network is not sufficiently developed. The variety of pineapple produced in Uganda is less attractive in comparison to others for example. It leads Uganda to enlarge its fruits crops to the organic fruits agriculture. Recently, The Ugandans have focused upon the drying process of fruits to develop their exportation business [10,14].

Country	Exports in US$ million
Côte d'Ivoire	210
Kenya	130
Ghana	34
Uganda	3

Table 1: Exports of fresh fruits and vegetables to EU (2000) [14]

1.1.3 Organic fruits agriculture in Uganda

In the past, the Ugandans had an important interest in preserving and respecting the nature. In addition, the fruits exportation business was never promoted due to colonial land occupation. These two reasons can explain why the backbone of the Ugandan agriculture has been structured by small holder producers (1.3 hectares/farmer) [15,16]. Consequently, the producers' incomes remained low. In view of all the elements listed above, they have allowed the soils to remain clean from fertilizers and chemical products. In 2011, around 227,000 hectares were under organic agricultural management in Uganda [16]. This organic agriculture could be developed thanks to the demand of developed countries in organic products; this was the driving force of the business. The developing countries are more and more aware of the benefits of these organic products. Thus, it offers a lot of opportunities within the organic sector. Indeed, the organic agriculture preserves the fertility of soils, it prevents water pollution and it sustains the agriculture [12,15].

The natural conditions have also a great influence on the development of this business such as high soil fertility, abundant rainfall and warm temperature. Thanks to these favourable natural conditions, it was then relatively easy for the farmers to produce organically. Despite some drawbacks such as the important workload represented by the manual weeding, the cost of coffee husk used as natural fertilizer which is expensive and the absence of organic local or regional market, the organic agriculture presents major benefits. It has a positive impact on the environment by allowing water retention, reducing soil erosion and enhancing the quality of the soil in terms of organic matter and agro biodiversity to mention a few advantages regarding the conventional agriculture. Organic agriculture allows the smallholder farmers to increase their income by ensuring a premium price for the export market sell [7,12]. However, it is very expensive to obtain the worldwide organic certification and it is hard to get it as there is very little information and trainings available. It is then quite difficult for the Ugandans to focus on the biological agriculture [12,15].

1.1.4 Benefits of the drying process and the particular case of the pineapples drying in Uganda

According to the Food and Agriculture Organization of the United Nations (FAO), 32% of the Sub-Saharan Africa population were victims of malnutrition in 2006. The losses related to post harvesting can reach 15 to 50% of the production and it leads to reinforce hunger [17]. Food losses lead to higher prices and energy waste as fruits or vegetables never reach the customer whom they were grown for. The drying process constitutes a reliable solution to overtake this problem, particularly the solar drying process. Thanks to the sunny weather, the conditions to carry out the solar drying process in Sub Saharan are favourable [3]. The solar drying represents a consistent way of food conservation in Sub-Saharan countries in comparison to canning and freezing which require a high energy demand and advanced technology to be implemented. It reduces the moisture content of the product, slows down the enzymatic activity and prevents the microorganisms' development responsible for further degradation [17,18].

Moreover, the solar drying presents two main advantages regarding other drying techniques. Firstly, it does not consume fossil fuel to work; thus, there is no production of greenhouse gases. The use of this technique is environmentally friendly and does not contribute to the global warming. Secondly, the dryer using this technology works for free as the only energy requirement is the solar energy [19].

More specifically, the fruits such as pineapples, mangoes and bananas are rapidly perishable. According to a study, these are the types of fruits that are predominantly dried in Uganda [20]. During the peak season, the price goes down and the supply quantity exceeds the demand on the local and regional markets; hence, the fruits need to be stored otherwise the excess production is going to decay. The drying process represents one of the solutions to reduce drastically the post harvest waste. In 2002, the total amount of dried fruits exported for Uganda was 90 Mt/year. The same year, the Ugandan's dried organic fruits export was around 30 Mt/year; there is a huge space for growth in the coming years. Actually, the estimated worldwide demand of organic dried fruits was evaluated at 164,000 Mt/year [10,12]. In order to understand the advantages and the constraints of this recent business over the conventional fresh fruits exportation, the following paragraph presents them. As this master thesis is focusing on the organic pineapple drying process, a closer look is taken at the organic pineapple crops.

On the one hand, the solar drying process creates employment for women and elderly people; thus, it leads to a better incomes allocation within the family. In addition, it provides a stable and constant price during the whole year and it avoids waste by promoting the drying of all pineapple sizes during the peak harvest season. The small size pineapples can be dried during the whole year as they are less attractive on the local market. It brings extra income as dried fruits are added value products. Thanks to the moisture reduction content, they can be stored for a longer time.

On the other hand, the solar drying process depends on the unpredictable weather conditions. In other words, these unstable climatic conditions can lead to losses during the drying operation. The cost of a dryer is expensive and the demand for dried fruits comes mainly from developing countries. Moreover, trainings and information are missing to provide sufficient knowledge to inspire farmers to be involved in the organic agriculture [11,20,21].

It can be noticed that additional economical studies such as business plans and trainings are required on the subject, especially the latter in terms of good manufacturing practices but also in Quality Control New dryers can also be implemented in order to increase the actual efficiency of this process which is quite recent in Uganda (1990’s). An improvement of the communication between all the farmers such as the creation of farmers association should be implemented [21]. This master thesis is consistent with this issue as it is focusing on the improvement of a solar drying process of pineapples in Uganda in partnership with the nongovernmental organisation: The Refugee Next Door©.

1.1.5 Non Governmental Organisation (NGO): The Refugee Next Door (RND)

The Refugee Next Door© (RND©) is a Belgian non-profit organisation active in Uganda. It was created in 2007; its mission is “to build a bridge between North and South and improve the life of the most vulnerable” [22]. RND© is focused on health, education and incomes by implementing actions to fulfil the needs of the most fragile and displaced people in Uganda. RND© actions are active in the field of primary education, vocational training and operational support in order to promote self-sustainability. RND© is 100% volunteer based and the bridge that RND© is trying to build relies on pillars such as transparency, involving local and international partners and promoting “direct impact projects”. Main RND activities are stated in 3 main projects [22,23].

- <u>Nursery and primary education: Saint Francis School and medial dispensary</u>

Since 2007, the objective of this project is to allow vulnerable children to go to school while their parents can be focused on working to increase the family incomes. RND© has for goals to build a new class every year in order to allow children to follow the integral nursery and primary education. Today, 8 classes are implemented and around 300 children benefit from this educational program. In 2012, a medical dispensary was built close to the school to provide basic medicine to children [22,23].

- Kitiibwa vocational training centre and restaurant

Around 40 women benefit from the vocational training. 3 different trainings are proposed: catering, tailoring and hairdressing. In 2012, a small take away restaurant owned by the students was created to allow the project to be sustainable financially [22,23].

- Farmer field school: pineapples business

This socio-economic project is to encourage the exportation of fair trade dried pineapples in the Belgian market. The objective of this project is to decrease the poverty within the farmers by promoting added value products to their conventional agriculture. For example, it provides them educational trainings related to pineapple drying. In 2014, Namakwanda farming cooperation (NFC) was founded; a cooperative that includes the farmers and producers of local fruits [22,23].

First, RND© has chosen to take part in an existing organisation by creating a partnership with Fruits Of the Nile (FON) which was created in 1991. In 2009, FON© sent 15,000 kg of dried fruits to EU [24]. By promoting the pineapples drying through farmers' community, RND© will create employment. Knowing that a family is composed of 10 people on average, a lot of people can take benefits from this process [3]. RND© works on improving the method of drying as well as the quality of the drying products. It works also on the enhancement of the efficiency of the solar dryers. RND© wants to export dried pineapples which fulfil the Belgian quality requirements. In this outlook, RND© started a partnership with the Ecole Polytechnique of the Université libre de Bruxelles to enhance the drying techniques and share information regarding the improvements with the NFC [22,23]. Thanks to this fair trade of dried pineapple project, the incomes of the farmers as well as those of the RND© are increased. RND© hopes to become financially independent from the private donors to sustain its development by a reliable incomes source [22,23].

Last year, Mathilde Lhote performed her master thesis on the development and the construction of a ventilated solar tunnel dryer in Uganda [25]. This ventilated solar tunnel dryer is wood-framed box composed of 2 parts connected in series: the heating zone and the drying zone. A detailed explanation of the ventilated solar tunnel dryer is presented in section 2.2.2. The development of the ventilated solar tunnel dryer was based on a design methodology implemented by Pauline Talbot as a part of her PhD thesis [26]. The objective of the PhD thesis was to develop a systematic procedure of ventilated tunnel solar dryer design that can be applied on different situations [25,26].

1.1.6 Ventilated solar tunnel dryer design methodology

The design procedure presented in Figure 2 is based on the solving of mass and energy balance equations. The latter are used to establish a mathematical model. The design procedure follows 3 steps. The first step is the scope statement that includes products specifications such as the nature of the product, the initial mass of fresh products and the expected final moisture content for example. During this first step, a data collection on the characteristics of the products was achieved. Different information such as initial moisture content, the required drying temperature as well as data related to the climate where the dryer needs to be implemented was collected. This data collection can be performed either by a literature review or laboratory experiments. Then, the model is completed by the three following design conditions [26].

- within the dryer, the relative humidity of the air should remain far below 100%;
- at the end of the heating zone, the averaged air temperature should reach an expected temperature during the drying. This temperature depends on the product that needs to be dried;
- the net energy captured in the drying part should balance the energy required to evaporate the water from the products when averaged over the drying time. Accordingly, the averaged air temperature at the end of the drying zone should reach the same expected temperature as the one at the end of the heating zone during the drying.

The model completed with these 3 following design conditions is alimented by the scope statement and the data collection in order to determine three parameters of the ventilated solar tunnel dryer. The second step allows to calculate the minimal required airflow which leads to determine the ventilation system. Finally, the length of the heating and the drying part are established [26]. It is imperative to control the drying temperature, the airflow and the humidity of the air during the drying because they are significant drying parameters. The drying temperature needs to be high enough to ensure good moisture evaporation while it needs to be lowered than the critical temperature above which the fruits or the vegetables develop a scorched taste. In the drying, rapid moisture removal is wanted. However, "case hardening" needs to be avoided. Due to a drying which is too fast, the surface of the fruits dries more rapidly than the core of the fruits. It follows that the surface becomes hard and inhibits the further moisture removal from the core of the fruit. This phenomenon takes place when the drying occurs too fast [27].

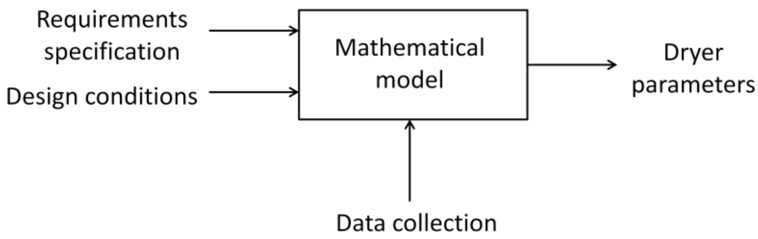

Figure 2: Design methodology established by Pauline Talbot [26]

This design methodology was implemented to build a solar tunnel dryer able to improve the quality of the dried pineapples as well as reduce the drying time [26]. In order to have a closer look to this procedure and its assumptions, the paper entitled "Ventilated tunnel solar dryers for small-scale famers communities: theoretical and practical aspects" can be read.

1.2 Objectives and strategy

1.2.1 Objectives

The objectives of this master thesis are multiple.

A first objective is to characterize the drying kinetics of pineapple slices as very few studies on this process are available in literature. The laboratory work was performed in the "Transferts, Interfaces et Procédés" laboratory at the Université libre de Bruxelles. On the one hand, this characterization is carried out to investigate the influence of two parameters on the drying kinetics: the air velocity and the slice thickness. On the other hand, this characterization is achieved to develop a mathematical model of the drying kinetics. Mathematical modelling is important regarding the design and optimisation method of dryers [28]. In future researches, this kinetics model will be implemented in the mathematical model used in the design methodology presented previously. Actually, the mathematical model previously introduced does not take into account the kinetics of the fruit drying [26].

A second objective of this master thesis is to investigate the opportunities of the enhancement of the pineapples drying process currently applied in Uganda. As previously mentioned, this master thesis is undertaken in collaboration with RND©. The aim to achieve is to make the process more reliable by improving the quality of the dried pineapples and increasing the production. In Uganda, the supervision of a new processing centre which was started by the previous volunteers needs to be ensured. On the new processing centre site, the construction of the ventilated solar tunnel dryers needs also to be supervised.

A third objective is to validate experimentally the design working conditions of the first ventilated solar tunnel dryer used by the organisation and to study the overall efficiency of the solar dryer. This dryer prototype was built last year by Mathilde Lhote as a part of her master thesis [25]. In order to complete this task, a set of experiments was carried out on site.

1.2.2 Strategy

In order to meet all the requirements of the expected objectives, the performed work was divided in 4 definite periods.

As a first step, a literature review was achieved in Belgium to have an overview of the drying process. Then, different specific aspects were investigated during this literature review. On the one hand, a research on the drying kinetics of pineapples was performed in order to prepare the laboratory work. On the other hand, specific attention was paid to the importance of the solar drying process in Uganda. This part of the literature review helped to understand the economical and social impact of this process recently implemented in Uganda. It facilitated to anticipate the main issues that could be encountered on the field and the work that needed to be performed. Then, this part of the documentation review helped in preparing the 2 months journey in Uganda. This literature review was focused on different aspects and allowed to have an overview of the situation related to the solar drying process, pineapples crops and the kinetics of drying.

In parallel to this literature review, a laboratory study was carried out to investigate the kinetics of drying pineapple slices in a tunnel dryer. From this laboratory study, a mathematical model was established to reproduce as well as possible the experimental data. This model is based on the resolution of the Fick's second law of diffusion [28]. The theoretical model allowed to determine the effective diffusion coefficient which characterises the water mobility through the product medium [29]. The impact of the airflow velocity and the pineapple slice thickness on the drying kinetics is investigated. The obtained values of the effective diffusion coefficient are discussed.

The part of the literature review related to the solar drying process and pineapples crops is presented in CHAPTER 1. The theoretical aspects of the drying process as well as the description of the ventilated solar tunnel dryer implemented in Uganda are included in CHAPTER 2. The energy balances taking place inside the dryer are also detailed in CHAPTER 2. The laboratory study and the establishment of the mathematical model used to identify an effective diffusion coefficient are presented in CHAPTER 3.

As a second step, the work on the enhancement of the drying pineapples process was achieved in parallel with the supervision of the implementation of a new processing centre in Uganda. All the practical work needed to be understood and implemented by the local Ugandans in order to be reproducible, sustainable and accepted within the society. This remark concerns especially the work on the improvement of the drying process and the establishment of the new processing centre. These 2 parallel tasks are described in CHAPTER 4 of this master thesis.

As a third step, a set of experiments was carried out on the ventilated solar tunnel dryer built last year on the field. This task was performed in parallel of the 2 previous ones during the stay in Uganda. The experiments were performed in order to verify if the design conditions expressed in 1.1.6 were satisfied during the drying. Then, the analysis of the results and the discussion about them were carried out. These results are included in CHAPTER 5 of this report. The efficiency of the ventilated solar tunnel dryer is also discussed in CHAPTER 5.

As a last step, the conclusions of the work and the outlooks to continue to improve the efficiency of the dryers on one side and of the drying operation on the other side are presented in CHAPTER 6.

CHAPTER 2: THEORETICAL ASPECTS OF THE DRYING PROCESS AND IMPLEMENTED DRYERS IN UGANDA

In this section, an overview of the theoretical aspects related to the drying operation is performed. Then, the solar dryers called solar cabinet dryers used by the company FON© are presented. As the ventilated solar tunnel dryer was implemented last year in Uganda, a closer look is taken on this kind of dryer. Hence, a detailed presentation of the solar tunnel dryer is included in this chapter. This kind of dryers is the prototype built last year in Uganda. Finally, this chapter ends by the different energy balances taking place within the dryer.

2.1 Overview of drying principles

The drying was the first technique used to preserve food as it prevents microbial attacks and enzymatic action to occur [30]. The aim of the drying operation is to decrease the moisture content within a product by allowing the evaporation of a liquid. Dehydrated food avoids microorganisms' development. In other words, it increases the shelf life of dried products. This technique presents different advantageous properties in comparison to conserving fresh food in its initial state. It lowers the weight, keeps the nutritive elements, creates an added value product and increases the conservation period to mention a few. Thus, a positive impact on the transportation cost can be noticed for example. The drying operation is one of the most energetic steps in the industry. It was estimated that it represents between 8% and 15% of the energetic cost of the manufacturing [29]. This master thesis focuses on the pineapple drying process in Uganda. The tropical Ugandan climate is warm and humid [3]. High temperatures and high humidity are detrimental conditions for fruits and vegetables conservation. These conditions promote fruits and vegetables degradation, thus the solar drying technique plays a vital role in developing tropical countries in terms of preventing post harvest waste [17,18].

The drying is a unit operation which consists of the liquid removal from a product to generate a solid product by enabling a phase change. Although different kinds of drying operation exists, such as freeze-drying in which the product is frozen and then it is dried by ice sublimation, this master thesis is focused mainly on the heat drying also called thermal drying [31]. The phase change occurring during the thermal drying is the liquid evaporation while it is the sublimation during the freeze-drying [19,29].

During the drying, two important phenomena take place simultaneously: the heat transfer from the source to the product which allows the liquid evaporation and the released vapour elimination [29]. The liquid evaporation occurs in 2 successive steps: first, the moisture content moves by diffusion from the core of the product to its surface and then from the latter to the surrounding environment. The evaporating rate depends on the state of the product and its moisture content [32]. It is important to identify the rate controlling factor during the drying operation in order to develop an accurate and reliable model of the transfer. In drying, the controlling rate factor can be either the internal diffusion or the external diffusion. According to V. Belessiotis, E. Delyannis [33], the evaporation is the step which consumes the highest amount of energy during the drying.

As this master thesis focuses on the solar drying process of pineapples, the energy supply is the solar energy. Thus, the heat supply to the product to allow the liquid evaporation can be either direct, it means that the product undergoes directly the solar radiations or it can be indirect, the product is exposed to a hot airflow [19]. A combination of both effects can also be implemented [29]. The vapour elimination can be performed by natural or forced convection. Two different ways of processing the drying exist; the drying operation can be achieved by a batch or continuous process. As previously mentioned, the aim of the drying is to reduce the moisture content of the product by bringing the necessary heat to evaporate the required amount of liquid. The necessary heat is determined by the latent heat of vaporisation of the liquid. In the case of pineapples drying, the liquid that needs to be evaporated is the water. The latent heat of vaporisation of water at 60°C is 2358kJ/kg [34]. Thus, the drying operation involves a heat and mass transfer.

The aim of drying is to enable the evaporation of the liquid, generally water, by bringing the required heat. It has to be achieved as economically as possible. The minimal required heat quantity per unit time is written Q_{evap} (W) and it can be calculated with Equation (2-1) combining an energy and mass balance [26]. The required heat quantity per unit time is directly determined by the mass of fresh products m_{fresh} (kg), the mass latent heat of water vaporisation $\mathcal{L}_w$ (J/kg), the drying time t_d (s), the water content that needs to be released. This is determined by the difference between initial moisture content X_0 (kg of water/ kg of dry matter) and the final moisture content X_f (kg of water/ kg of dry matter) in order to ensure a storage without degradation [17].

$$Q_{evap} = m_{fresh} \frac{(X_0 - X_f)\mathcal{L}_w}{(1 + X_0)t_d} \tag{2-1}$$

Most of the solar dryers used by FON© in Uganda are simple cabinet dryers as their building and operating costs are low [24]. Moreover, these dryers are user friendly and require simple maintenance. They are direct dryers with natural convection. They appear to be widely used in a family scale [24,30]. However, the temperature control and the drying rate may be limited [30]. It leads to an inhomogeneity and a risk of high moisture content in the air within the dryer. Thus, the drying conditions are hardly manageable. They are widely used for small scale fruits and vegetables drying. These passive dryers and the active pilot dryer, which is a tunnel solar dryer are presented in the following section [32].

2.2 Solar Dryers

2.2.1 Solar dryers implemented in Uganda by FON©

The cabinet solar dryers are timber-framed as shown in Figure 3. The specific dimensions of the dryers used in Uganda are expressed in Figure 4. The top of the dryer is covered by anti-UV transparent plastic foil in order to avoid fast spoilage of the plastic cover [35]. The dryers are built on 6 feet at certain height to prevent fast degradation due to contact with the ground. The bottom of the dryer is constituted of different layers of insulator materials: a first layer of papyrus is laid down; then a layer of dried grass and finally an iron sheet which is black painted. The iron sheet is painted in black in order to increase the heat absorbance [36]. The trays are made of mosquito net and the pineapples are put on them inside the dryer. They usually put 2 trays within the dryers with 7.5kg of fresh pineapple slices on each tray on average. On one side of the framework, doors are built to facilitate the insertion of the trays within the dryer. On the 2 small sides of the dryer, a small band area is covered with mosquito net to allow a natural convection to occur. All the materials are locally available except the anti-UV plastic foil and the mosquito net which are imported from EU.

Figure 3: Simple cabinet dryers used by Fruits Of the Nile organisation

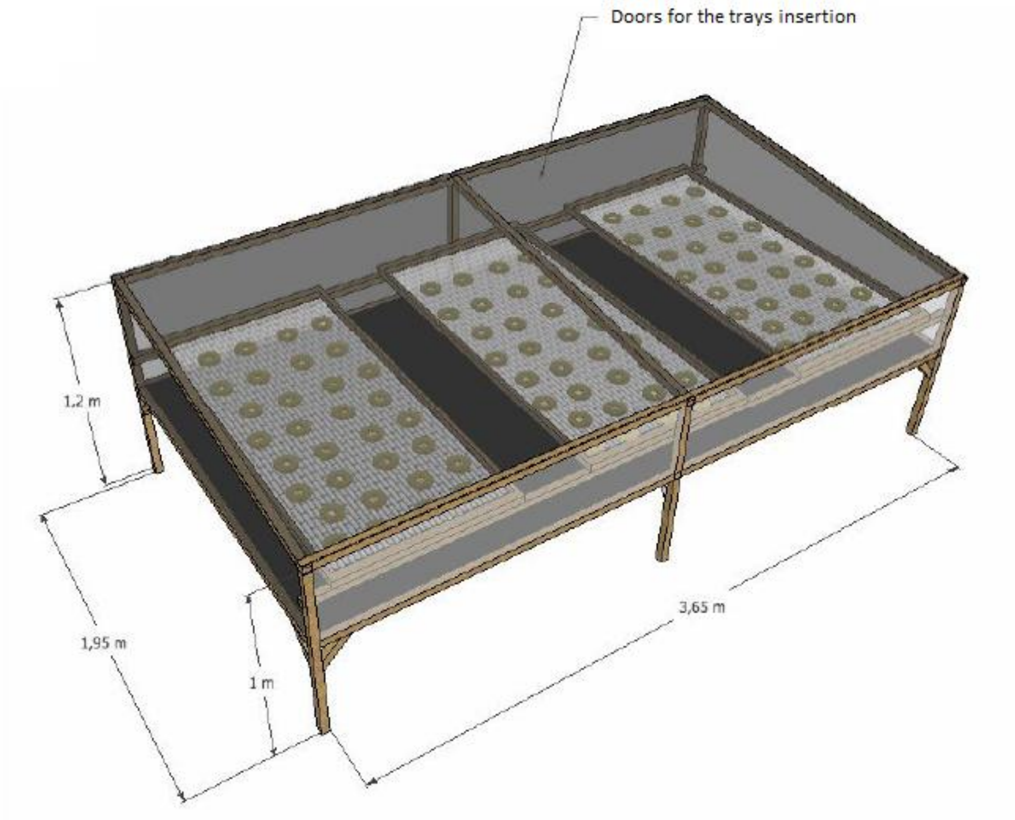

Figure 4: Plan of passive cabinet dryers used by FON© farmers in Uganda [25]

2.2.2 Ventilated tunnel solar dryer description

In order to improve the efficiency of the drying process and to increase the quantity and the quality of the drying products, The Refugee Next Door© has asked for help to the Ecole Polytechnique of the Université libre de Bruxelles. As natural convection solar dryers present limitations in terms of temperature control, the study was centred on the development of forced ventilated dryer. These solar dryers can be of various types. In that context, Mathilde Lhote achieved last year the building of a new ventilated solar tunnel dryer [25]. A ventilated solar tunnel dryer is a ventilated greenhouse; it means it takes advantage from the greenhouse effect as well as the forced convection of air. This prototype was built in Uganda based on a design methodology previously established by Pauline. This design methodology is briefly explained in the first chapter (1.1.6). This new constructed dryer had to fulfil the three design conditions stated in chapter 1. If these three conditions are satisfied, an efficient and uniform drying is expected to take place within the dryer. Indeed, all the products will be in contact with hot air which is far from its water saturation concentration [26].

As forced convection takes place within the dryer, it allows a better control of the drying parameters in comparison to the low buoyancy of the cabinet solar dryer introduced previously [25,26]. The forced airflow is controlled by a 4 small fans connected in series which are inserted on one side of the dryer. They are supplied by a photovoltaic cell. It is also worth mentioning that a tunnel solar dryer is a dryer which combines both energy inputs. It allows the product to dry by both phenomena: direct and indirect energy supply. Indeed, the product is submitted to the direct solar radiations and to the hot air flowing from the heating part. The tunnel solar dryer operates in a discontinuous way [29].

The tunnel solar dryer is composed of 2 zones: the heating and the dry zone. They are connected in series such as shown in Figure 5. The air is entering by the left in Figure 5. The airflow is heating up from the entrance of the heating zone towards the dry zone. This increase in temperature is possible thanks to solar radiations and the greenhouse effect which is present within the dryer. The bottom of the dryer is constructed of a layer of papyrus, superimposed by a layer of dried grass and finally a black painted iron sheet used as a heat absorber [36]. The two first layers ensure the bottom of the dryer to be insulating. The products are laid on trays in the dry zone whereas the heating zone is product-free. The drying zone is designed to support 4 trays of 7.5kg of fresh pineapple slices each (30kg in total) [25]. The products undergo both direct solar flux energy and indirect energy from the hot airflow. The released water vapour is carried away by the forced airflow [29]. The exit side is completely covered by a mosquito net while the entire top is covered with an anti-UV transparent plastic foil. It is important to ensure an airtight structured to prevent flags and insects to enter the dryer and to reduce the heat losses as well. Two pictures of the ventilated solar tunnel dryer implemented in Uganda are shown in Figure 6.

Though the price of the new ventilated solar tunnel dryer is more expensive than the one of the usual cabinet dryers, RND© has chosen to trust this new kind of dryer for different reasons. The price of the ventilated solar tunnel dryer costs around 450 US$ (carpenter work included) while the price for the cabinet dryers is 300 US$ (not specified if the carpenter work is taken into account) [24]. However, it ensures an enhanced quality of the dried product as the drying operation is better controlled. Consequently, it reduces the waste that can be produced during the drying operation. Although its ground surface is twice higher than the one of the conventional cabinet dryers, it compensates this drawback by allowing to insert a quantity two times higher (30 kg) of fresh pineapples than in the quantity in the cabinet dryers (15 kg). Moreover, Ugandans do not have restriction regarding the area. They still have a lot of available space.

In order to facilitate a better understanding of the energy transfers taking place during the drying operation, the following sub chapter details the energy balances occurring within the ventilated solar tunnel dryer.

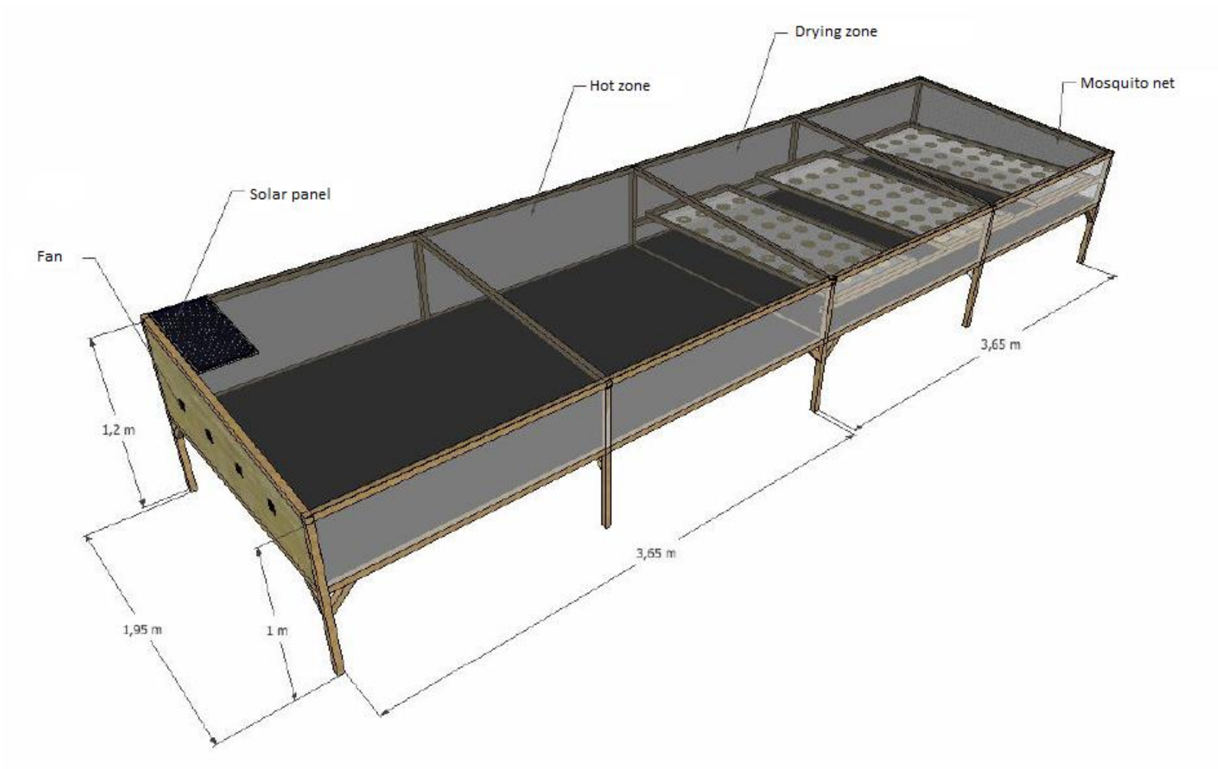

Figure 5: Plan of the tunnel solar dryer made in Uganda in February 2015 [25]

Figure 6: Pictures of the tunnel solar dryer in Uganda

2.3 Energy balances within the ventilated solar tunnel dryer

2.3.1 Introduction

All the heat fluxes taking place within the drying process are described in this section. Before introducing the energy balances taking place within the ventilated solar tunnel dryer, the three modes of heat transfer are explained as a reminder: the convection, the conduction and the radiation. The convection is a physical heat transfer process. The energy is transferred by fluid movement and molecular diffusion. The conduction is the heat transfer taking place within a medium or between 2 media in contact with a temperature gradient. There is a heat transfer by thermal radiation as well. All bodies use to emit and receive electromagnetic radiation. This energy transfer depends on the body temperature and its surface nature. The equations of these 3 modes of heat transfer are presented in Equations (2-2) to (2-4) where the different variables are described in Table 2 [37,38].

$$q_{conv} = h(T_w - T_\infty) \quad (2\text{-}2)$$

$$q_{cond} = \frac{k}{e}(T_{ini} - T_{end}) \quad (2\text{-}3)$$

$$q_{rad} = \varepsilon\sigma T^4 \quad (2\text{-}4)$$

Symbol	Definition	Units
q_{conv}	Convection heat transfer	W/m^2
h	Heat transfer coefficient	$W/(m^2K)$
T_x	Absolute temperature	K
q_{cond}	Conduction heat transfer	W/m^2
k	Thermal conductivity	$W/(\ m\ K)$
e	Thickness	m
q_{rad}	Radiation heat transfer	W/m^2
ε	Emissivity	*[0,1]*
σ	Stefan-Boltzmann constant	$W/m^2\ K^4$
T	Absolute temperature	K

Table 2: Variables description of equations (2-2), (2-3) and (2-4)

2.3.2 Balance equations within the ventilated solar tunnel dryer

The different heat transfers taking place within the ventilated solar tunnel dryer are represented in a flow cross section of the heating and the drying parts, respectively in Figure 7a and Figure 7b. In the heating part, a fraction λ of the direct and diffuse solar radiations (F_S) acts on the black flat bottom of the dryer by heating it while the faction 1-λ is captured by the outer surface of the plastic foil. λ is a parameter which depends on the plastic and wood types used to build the framework. The black floor is assumed to be an insulator and consequently it is not heated or heat is not lost by conduction. A greenhouse effect takes place within the dryer as the black floor heats up; thus an infrared radiation exchange occurs between the black floor and the inner part of the plastic foil ($F_{IR,in}$). A convective heat transfer takes place between the floor and the air within the dryer ($F_{conv,in}$) but also between the inner surface of the plastic foil and the air inside the dryer ($F_{conv,p}$). The outer surface of the dryer captures also the infrared radiation fluxes from the atmosphere ($F_{IR,atm}$). A conduction transfer happens through the plastic thickness ($F_{cond,p}$). It is defined as positive when the conduction transfer occurs from inner surface of the plastic foil towards the outer surface. Infrared radiations are lost from the top of the plastic to the atmosphere ($F_{IR,out}$) and there is also loss by convection between the outer surface of the plastic foil and the atmosphere ($F_{conv,out}$). In the drying part, the same heat transfers are taking place excepted on the black floor where an evaporation flux occurs between the pineapples and the atmosphere within the dryer (F_{evap}). This term represents the energy necessary to reduce the moisture content within the product averaged on the drying time [26,39].

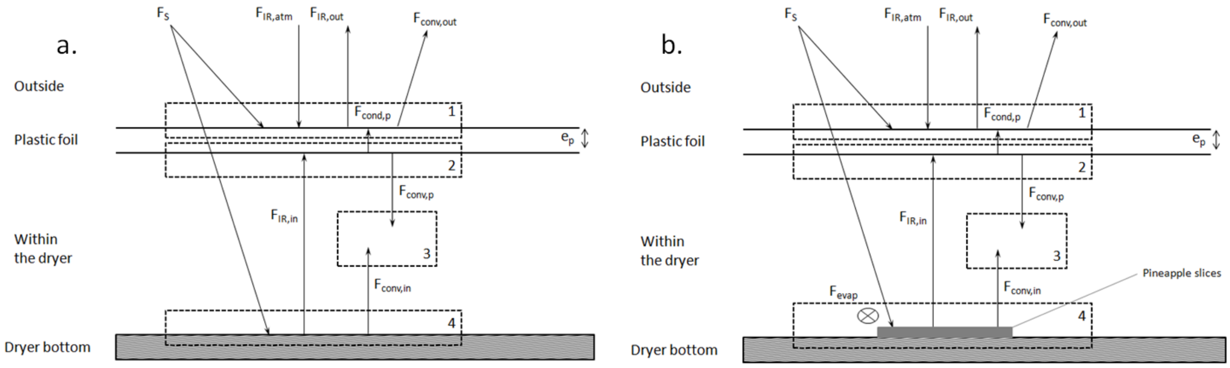

Figure 7: Energy fluxes taking place within the dryer represented in a transversal cut of the heating part (a) and drying part (b)

The units of all the energy fluxes are defined as W per m² of floor area or per m² of plastic surface. In order to express in a clear way, the balance equations, 4 frames are defined in Figure 7. These frames are used to make the balance between entrance fluxes and outgoing fluxes. It is important to mention that all the emitting surfaces are considered as black bodies, it means that the emissivity ε of the black floor and the plastic floor are considered to be equal to 1 [40,41]. The detailed expressions of the different energy fluxes are described in Table 3 with T_{fl}, T_{air} and T_{amb} the temperature of the black floor of the dryer, the temperature of the air within the dryer and the ambient temperature respectively. $T_{p,i}$ and $T_{p,o}$ are the temperatures on each side of the plastic foil, $T_{p,i}$ is the temperature on the inner surface of the plastic cover whereas $T_{p,o}$ is the temperature on the outside surface of the plastic cover. The thickness of the plastic foil is described by e_p and k_p is its thermal conductivity. The heat transfer coefficients are written by $h_{p,i}$, $\mathrm{h_{p,o}}$and h_{fl}; σ is the Stefan-Boltzmann constant for the radiation flux. In the evaporation flux equation, the initial and final moisture contents are described by X_0 and X_f; the drying time is expressed by t_d and the mass latent heat of vaporization of water and the mass of fresh products disposed by floor area are represented correspondingly by $\mathcal{L}_w$ and M_s ($M_s = \frac{m_{fresh}}{L_D W_D}$ with L_D and W_D which are respectively the length and the width of the drying part) [26,39].

Energy flux (W/m²)	Detailed expression	
$\boldsymbol{F_s}$	$\mathrm{F_s}$ varies according a sinusoidal function along the day [26]	
$\boldsymbol{F_{IR,in}}$	$F_{IR,in} = \sigma\,(T_{fl}^4 - T_{p,i}^4)$	(2-5)
$\boldsymbol{F_{IR,atm}}$	$\mathrm{F_{IR,atm}}$ is considered constant and equal to its mean diurnal value [25,26]	
$\boldsymbol{F_{conv,in}}$	$F_{conv,in} = h_{fl}\,(T_{fl} - T_{air})$	(2-6)
$\boldsymbol{F_{conv,p}}$	$F_{conv,p} = h_{p,i}\,(T_{p,i} - T_{air})$	(2-7)
$\boldsymbol{F_{cond,p}}$	$F_{cond,p} = \frac{k_p}{e_p}\,(T_{p,i} - T_{p,o})$	(2-8)
$\boldsymbol{F_{conv,out}}$	$F_{conv,out} = h_{p,o}\,(T_{p,o} - T_{amb})$	(2-9)
$\boldsymbol{F_{evap}}$	$F_{evap} = \frac{M_s}{1+X_0}\,\frac{X_0 - X_f}{t_d}\,\mathcal{L}_w$	(2-10)
$\boldsymbol{F_{IR,out}}$	$F_{IR,out} = \sigma\,T_{p,o}^4$	(2-11)

Table 3: Detailed expressions of the energy fluxes taking place within the dryer and between the dryer and the atmosphere

Thanks to 4 different frames drawn in Figure 7, it is possible to express the balance equations for the heating part: Balance equations on the outer and inner surface of the plastic foil, within the dryer and at the level of the black floor. First, general energy balance equations are presented such as Equations (2-14,16,18,21). Second, the detailed equations are described in Equations (2-15,17,19,22) based on Table 3. As the natural convection is assumed to be predominant on the forced convection, the convective heat transfer coefficients can be calculated by using the Nusselt and Rayleigh numbers defined in Equation (2-12) and (2-13) [26,37,41].

$$Nu = \frac{h\,D_h}{k_a} = 0.4\,Ra^{0.25} \tag{2-12}$$

$$Ra = Gr\,Pr = \frac{\beta_a\,g D_h^3 \Delta T}{\nu_a^2}\,\frac{\nu_a \rho_a c_{p,a}}{k_a} \tag{2-13}$$

Nu is the Nusselt number while Ra, Gr and Pr are Rayleigh, Grashof and Prandtl numbers respectively. The thermal conductivity of the air is described by k_a and D_h is the hydraulic diameter of the transversal cut of the flow. β_a is the thermal expansion coefficient of the air, g is the standard acceleration due to gravity, ν_a is the kinematic viscosity of air, ρ_a is the air density and $c_{p,a}$ is the heat capacity of the air.

Nusselt is a dimensionless number which is defined by the ratio of conductive to convective thermal resistance while Rayleigh number is associated to natural convection. Rayleigh dimensionless number is described as the product of the Grashof and Prandtl dimensionless numbers [37]. The correlations defined previously are appropriate for the considered geometry nevertheless many correlations exists in literature depending on the specific case that needs to be solved [37,41,42].

1 Energy balance equation at the level of the outer surface of the plastic foil

$$(1-\lambda)\, F_s + F_{IR,atm}\, R + F_{cond,p} \;=\; F_{IR,out} + \; F_{conv,out} \tag{2-14}$$

$$(1-\lambda)\, F_s + F_{IR,atm}\, R + \frac{k_p}{e_p}\,\left(T_{p,i} - T_{p,o}\right)R = \sigma\, T_{p,o}^4 R + h_{p,o}\,\left(T_{p,o} - T_{amb}\right) R \tag{2-15}$$

R is the aspect ratio between the plastic foil area and the black floor of the dryer as shown in Figure 8 and described by $R = \frac{0.4+0.6+1.96}{1.95} = 1.52$. An increase of this aspect ratio will lead to higher losses as the infrared radiation are the main losses within the system.

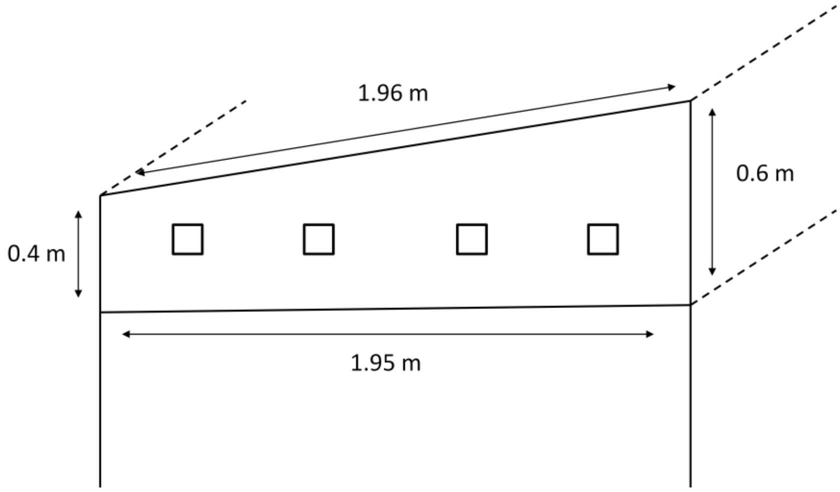

Figure 8: Transversal cut of the ventilated solar tunnel dryer used in Uganda [25]

2 Energy balance equation at the level of the inner surface of the plastic foil

$$F_{cond,p} + F_{conv,p} = F_{IR,in} \tag{2-16}$$

$$\frac{k_p}{e_p}\,\left(T_{p,i} - T_{p,o}\right)R + h_{p,i}\,\left(T_{p,i} - T_{air}\right)R = \sigma\,\left(T_{fl}^4 - T_{p,i}^4\right) \tag{2-17}$$

3 Energy balance equation within the dryer

$$P = F_{conv,p} + \; F_{conv,in} \tag{2-18}$$

$$P = \; h_{p,i}\,\left(T_{p,i} - T_{air}\right)R + \; h_{fl}\,\left(T_{fl} - T_{air}\right) \tag{2-19}$$

P is the energy flux transmitted to the air within the dryer thanks to the black floor and the inner surface of the plastic foil. This energy flux is expressed by Equation (2-20) [26].

$$P = A_{air}\; c_{p,a}\,\frac{dT_{air}}{W_D dz} \tag{2-20}$$

4 Energy balance equation on the black floor

$$\lambda\, F_S = F_{IR,in} + F_{conv,in} \tag{2-21}$$

$$\lambda\, F_S = \sigma\, (T_{fl}^4 - T_{p,i}^4) + h_{fl}\, (T_{fl} - T_{air}) \tag{2-22}$$

These 3 first energy balances are also valid for the drying part. However, the energy balance Equations (2-21,22) at the black floor level need to be adapted by taking the evaporation flux into account as expressed in Equations (2-23,24).

$$\lambda\, F_S = F_{IR,in} + F_{conv,in} + F_{evap} \tag{2-23}$$

$$\lambda\, F_S = \sigma\left(T_{fl}^4 - T_{p,i}^4\right) + h_{fl}\left(T_{fl} - T_{air}\right) + \frac{M_s}{1 + X_0}\,\frac{X_0 - X_f}{t_d}\,\mathcal{L}_w \tag{2-24}$$

Thanks to the last part of this chapter, the heat transfers occurring within the designed ventilated dryer could be presented. It helps to understand which equations were considered to define the dimensions of the dryer. This part helps to calculate the overall efficiency of the dryer in the following CHAPTER 5. CHAPTER 3 is presenting the investigations performed in Laboratory in order to study the kinetics of drying pineapple slices.

CHAPTER 3: CHARACTERIZATION OF THE DRYING KINETICS OF PINEAPPLE SLICES IN LABORATORY

3.1 Introduction

Many studies have been conducted on food drying; however only a few have been performed on the drying kinetics of pineapples. S. E. Agarry et al investigated the effect of blanching temperature-time combinations on the drying kinetics of pineapples [43]. J. F. Nicoleti et al. studied the air-drying kinetics of fresh and osmotically pre-treated pineapples at different temperatures and air velocity as well as under constant product temperature drying conditions [28]. M. S. Rhaman and J. Lamb investigated the air drying rates of fresh and osmotically pre-treated pineapple slices at fixed air drying conditions for all experiments [28]. M. S. Uddin et al. reported the value of effective diffusion coefficients for fresh and osmotically pre-treated pineapples [28].

In this chapter, a contribution to a better understanding and modelling of the drying kinetics of pineapple slices is presented. It is worth mentioning that the drying kinetics of all kinds of food cannot be described by the same equation and thus by the same model. Indeed, the initial moisture content and the transport phenomena taking place during the drying operation are different [43]. Hence, many studies on food drying have been performed to propose suitable models regarding the desired product to dry. In order to design and optimise dryers, mathematical modelling of the drying operation is very convenient [28]. Different models such as the shrinking core model or the thin layer model can be implemented to describe the drying process of a product [29]. As a reminder, the drying is defined by two successive steps: heat transfer from the heating source to the product and a mass transfer from inside of the product to the gas-liquid interface and finally from the interface to the surrounding environment [32]. The moisture travels from the interior of the product to the interface by diffusion as well as the displacement from the interface to the air [32]. These 2 steps can be characterised by an internal and an external resistance.

According to Nicoleti, J.F. et al [28], Jangam, S et al [44] and Akpina, E. [45], drying of food and agriculture products can be assumed to be controlled exclusively by internal diffusion. Thus, the model used in this master thesis is the thin layer model which neglects the external diffusion [28]. The thin layer model which is based on the solution of Fick's second law of diffusion is the most broadly investigated theoretical model to describe the drying kinetics. Based on the analytical solution of the Fick's second law and the experimental data collection, it permits to calculate the effective diffusion coefficient [28]. The effective diffusion coefficient characterises the mass transport of moisture (liquid or vapour) within the material [29,46]. A lot of studies reported the influence of the drying temperature on the effective diffusion coefficient whereas very few studies investigated the effect of the slice thickness of the product. Tinuade J. Afolabi et al evaluated the effect of the thickness and the air temperature on the effective diffusion coefficient for ginger slices [47].

In this framework, different experiments were performed in order to investigate the reliability of the assumption made by several researchers that the external diffusion can be completely neglected [28,44,45]. According to Madamba et al, the influence of the air velocity on the drying can be neglected. They concluded that the resistance to the movement of the water from the product surface to the drying medium is statistically less important than the internal resistance [48]. However, the effects of the air velocity and the thickness of pineapple slices on the drying kinetics were investigated in this laboratory work. During all the experiments, it is worth mentioning that the temperature of the airflow was kept constant at 65°C. The results are presented and discussed in the section 3.3. Then, the development of a mathematical model to describe the drying operation has been achieved by using Mathematica 7$^{©}$as software. The development of this model is based on the thin layer model. Based on this theoretical model and the experimental results, the effective diffusion coefficient can be calculated. The obtained values of the effective diffusion coefficient are discussed in this chapter.

3.2 Materials and methods

3.2.1 Experimental setup

The experimental tunnel dryer which is used to perform the experiments was initially built by Laurent Spreutels for the Baker's yeast pellet drying [49]. It stands in the TIPs laboratory at the Université libre de Bruxelles. This experimental setup was adapted for the pineapple slices drying. A schematic representation is presented in Figure 9. The air is blown from the compressor (1) towards the transparent plastic pipe. The pipe has a square flow cross section of 110.25 cm². A rotameter (2) is present in order to ensure a precise and reliable measurement of the airflow. The air is heated up by going through the heating part (3). A heating device is regulated using a Pt 100 resistor placed in the flow in front of the holder sample device (9). The holder sample device was initially a grid. Then, it was replaced by a round mosquito tray in order to be as close as possible to the conditions met on the field as shown in Figure 10.

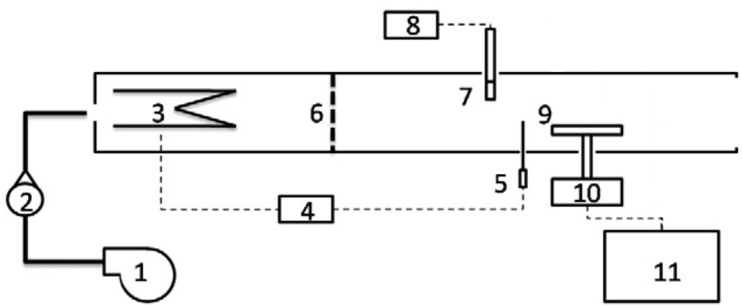

Figure 9: Scheme of the experimental setup [49]

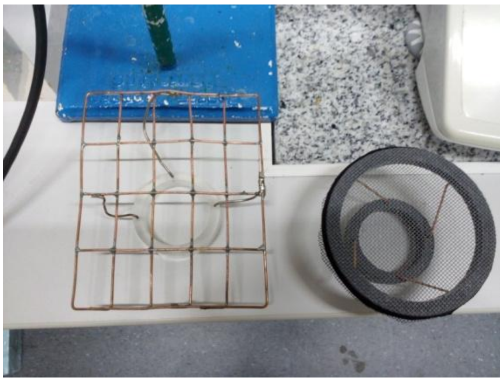

Figure 10: Sample holders. On the left, the initially grid sample holder and on the right, the new support

The temperature regulation is ensured by a heating regulator (4) and a control thermocouple (5). A gas diffuser (6) ensures the homogeneity of the airflow. A hygrometer probe (7) (Testo 650 from Testo, A.A., Ternat, Belgium) is used to measure the relative moisture content of the air and the temperature. The precision of the hygrometer is 0.1% for the relative moisture of the air and 0.5°C for the temperature measurement. These measurements are displayed on the hygrometer acquisition device (8). The pineapple slice is laid on the holder and its weight is continuously recording thanks to a precision (0.01g) scale Sartorius CPA22025 (10) (S.A. Sartorius Mechantronics, Vilvoorde, Belgium). As the precision is very small regarding the weighted mass, the error is not represented on the different following figures. This scale is connected to a computer (11) in order to record the weight every 5 minutes. For all the experiments, the room was closed to avoid disturbances. A picture of the experimental setup is shown in Figure 11. A mandolin was used to cut the pineapple slices precisely in order to obtain the required thickness.

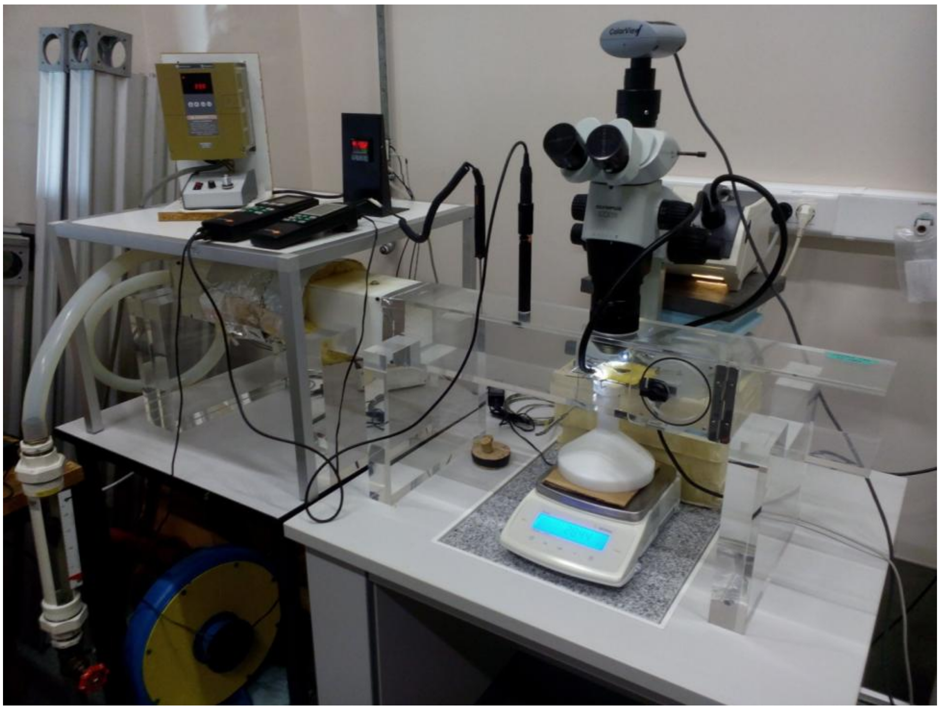

Figure 11: Experimental setup in November 2015

3.2.2 Experimental procedure

Uganda is a producer of Smooth Cayenne pineapple variety [10,25]. These are the pineapples used by Fruits of the Nile© and the Refugee Next Door© in Uganda. As the pineapples are less competitive than other pineapple crops, it was impossible to find this variety of pineapples in Brussels, more particularly in mabru©, the early morning market. Thus, 7 experiments were performed by using two different varieties. For the 3 first experiments, the Special Cayenne pineapples produced in Ghana were used while DAM Extra pineapples from Côte d'Ivoire were used for the 4 last experiments. The experiments were all carried out at 65°C. For each experiment, only one slice of pineapple was introduced on the sample holder. The pineapple slices was dried during 7 to 10 hours until it reached the equilibrium with the air within the dryer. In other words, it was dried until its mass reached a constant value. Different airflows were investigated during these experiments. The airflow rates implemented were 8, 13, 17 and 18 Nm^3/h.

After peeling the pineapples, a mandolin was used to cut the slices precisely. Slices of 4, 6 and 8 mm were cut. Before each experiment, at least 2 slices in addition to the one used in the tunnel dryer were cut. These slices were weighted thanks to a precision scale SARTORIUS© BP2215 ($\pm$1.5mg for a mass higher than 20g) and then introduced in the oven (MEMMERT© modell400, D06060) for 24h at 70°C for desiccation [25,50]. After 24h in an oven, the pineapple slices were weighted again in order to determine the initial moisture content on a dry basis (d.b). For each experiment, more than one slice was introduced in the oven to investigate the homogeneity of the moisture content within a pineapple as well as among different pineapples.

In order to obtain steady-state conditions within the tunnel dryer, the airflow and the heater are turned on before introducing the pineapple slice. They are already set to the expected airflow and temperature values. As soon as the pineapple slice is laid on the support, the weight acquisition needs to start by the launching program on the computer. At the end of the experiment, the heater is turned off before the airflow blower to avoid damaging of the experimental device.

3.2.3 Data treatment

The initial moisture content can be deduced from the desiccation during 24h at 70°C. The initial moisture content X_0 is expressed on a dry basis (d.b) as the ratio of the water content weight to the dry matter weight as shown in Equation (3-1) [33]. The initial moisture content is expressed in kg of water per kg of dry matter. m_i and m_f are respectively the initial mass introduced in the oven and the final mass recovered from the oven. The water content is written m_w. The average initial moisture content obtained from the experiment is $X_0 = 4.8$ (d.b). For each experiment, the dry mass of the pineapple slice laid on the grid support can be determined based on its initial mass (M_0) and its initial moisture content (X_0) [49]. The dry mass M_d formula is presented in Equation (3-2).

$$X_0 = \frac{m_i - m_f}{m_f} = \frac{m_w}{m_f} \tag{3-1}$$

$$M_d = \frac{M_0}{1 + X_0} \tag{3-2}$$

At any time during the experiment, the moisture content $X(t)$ (d.b) of the product can be expressed in function of the mass measurement $M(t)$ [49]. The moisture content equation is written in Equation (3-3). The drying rate J can then be deduced from $X(t)$ thanks to Equation (3-4). It is expressed as the time derivative of the moisture content in kg of water evaporated per kg of dry matter per unit of time [44].

$$X(t) = \frac{M(t)}{M_d} - 1 \tag{3-3}$$

$$J = -\frac{dX}{dt} \tag{3-4}$$

The influence of the slice thickness and the air flow velocity on the drying curves is discussed in this chapter. These drying curves are either the moisture content $X(t)$ (d.b) in function of the drying time or the drying rate J in function of the moisture content $X(t)$ (d.b). For the influence of the slice thickness on the drying curves, another drying curve is used. It presents the ratio of the masses written as $\frac{M(t)-M_f}{M_0-M_f}$ in function of $\frac{t}{H^2}\mathcal{D}_{eff,ref}$ to investigate the effect of the external diffusion. M_f is the final mass of the pineapple slice within the dryer, H is the thickness of the pineapple slice. $\mathcal{D}_{eff,ref}$ is chosen equal to $5\ 10^{-10} m^2/s$ as it is included in the range of values found in literature [44].

3.2.3 Experimental plan

The study of the influence of operating parameters (airflow velocity and thickness of the pineapple slice) on the drying kinetics was performed through seven experiments. The mathematical model with the help of the experimental results aims to calculate an effective diffusion coefficient of the pineapple drying [29]. The acquired values for the effective diffusion coefficient are discussed. The moisture content (d.b) evolution and the drying rate are also investigated. The conditions of the seven experiments which were carried out are presented in Table 4. The conditions of the experiments were carefully chosen to test the assumptions made by some researchers concluding that the external diffusion could be neglected [28,44,45]. All the experiments were achieved at a constant temperature of 65°C.

In order to illustrate the effect of the air velocity on the drying kinetics, four different air flow rates were carried out: 8, 13, 17 and 18 Nm^3/h. These four values correspond respectively to air velocities of 0.25, 0.41 0.53 and 0.56 m/s (considering the flow cross section surface of the tunnel dryer of 110,25 cm^2). In order to investigate the effect of the pineapple slice thickness, three different thicknesses were used among two varieties of pineapples: 4, 6 and 8 mm. During the experiment, the weight was measured every 5 minutes in order to evaluate the amount of water evaporated per time unit.

Experiment	Variety	Pineapple slice thickness (mm)	Airflow velocity (Nm^3/h)	Airflow temperature (°C)
1	Special Cayenne (SC)	8	18	65
2	Special Cayenne (SC)	6	13	65
3	Special Cayenne (SC)	4	13	65
4	DAM Extra (DAM)	6	17	65
5	DAM Extra (DAM)	6	13	65
6	DAM Extra (DAM)	6	8	65
7	DAM Extra (DAM)	4	13	65

Table 4: Experimental plan with operating parameters (airflow velocity, thickness of pineapple slice and airflow temperature)

3.3 Experimental results

3.3.1 Initial moisture content

The initial moisture contents of all the pineapples introduced in the oven are presented in Table 5. A variation of the initial moisture content between the same variety of pineapples can be noticed as it was expected. The initial moisture seems to depend on the ripeness of the fruit and also on the variety of pineapple. It seems also to depend slightly on the location within the fruits as a small variation within the same pineapple can be noticed. It indicates that a natural variability is present for the moisture content of the pineapple. These results highlight the natural variability that can be present within the pineapple and remind that the further results are discussed accordingly.

Experiment	X_0 slice 1	X_0 slice 2	X_0 slice 3	X_0 slice 4	Average initial moisture content
1	5,2	5,6	5,8		5,5
2	5,4	4,7	5,2	5,3	5,1
3	4,9	4,4			4,6
4	3,8	4,0	3,8		3,9
5	5,4	5,1	4,9		5,1
6	5,4	5,2	5,6		5,4
7	4,0	3,9	4,0		4,0
Average					**4,8**

Table 5: Initial moisture content of pineapple slices

3.3.2 Influence of the thickness on the drying curves

The effect of the pineapple slice thickness on the drying curves is shown in Figure 12. During the experiments, it was noticed that thinner slices causes shorter drying times as expected. This observation is significant for the Extra DAM variety while it is less pronounced for the other one. Actually, the distance that moisture needs to travel is becoming smaller, thus the evaporation occurs faster [47]. In Figure 12, it can be seen clearly that the first part of the slope of the moisture content can be approached by a straight line. It could indicate that the evaporation is first influenced by the external diffusion and the internal diffusion for a short period of time [29]. It seems that both resistances have to be considered.

In order to investigate this assumption, Figure 13 is presented. If the diffusion was only limited by the internal diffusion, it is expected that all the curves in Figure 13 are placed on each other. In Equations (3-13), (3-14) and (3-15), it can be understand that this ratio $\frac{M(t)-M_f}{M_0-M_f}$ depends only on $\frac{t}{H^2}$. $\mathcal{D}_{eff,ref}$ is added in the characteristic time to have a dimensionless number. Although the two drying curves of slice thickness of 4mm are placed on each other, not all of them are superimposed. The two drying curves of slice thickness of 4 mm dried at the rate; it can be explained by the ripeness of the fruits. As all the drying curves are not placed on each other, it suggests that the internal diffusion is not strictly the controlling rate; both external and internal resistance have to be considered.

This last observation is discussed with the influence of the air velocity as the external resistance depends on the air velocity [50]. In Figure 12, a last observation regarding the moisture content can be carried out. At the end of the experiments, the moisture content is higher than 0 for all the performed experiments except for the experiment 3 (65°C – 4 mm – 13Nm³/h). At these conditions, all the water cannot be evaporated.

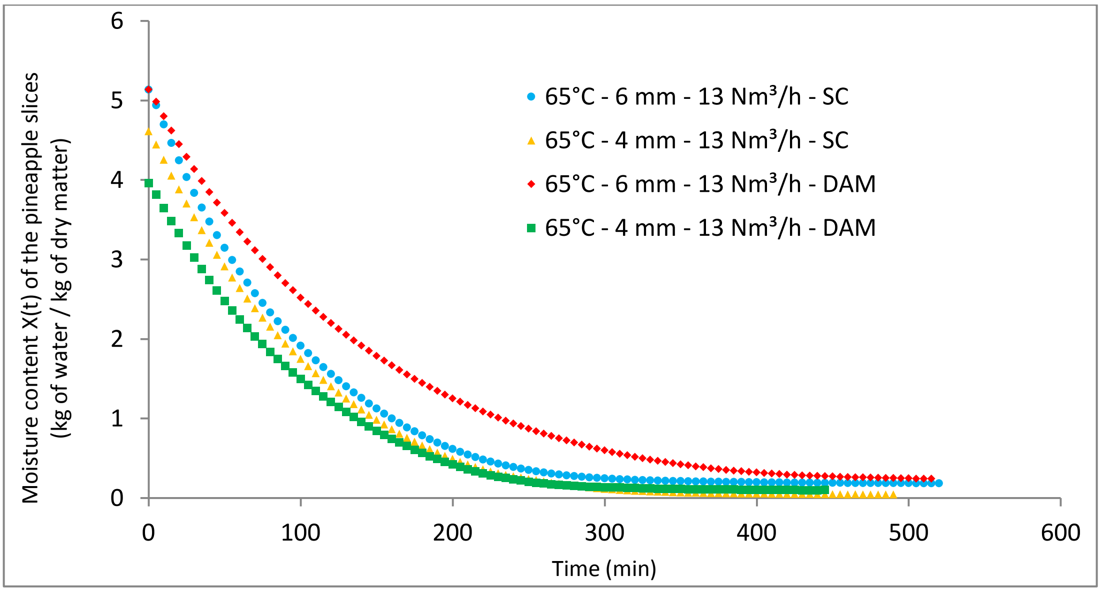

Figure 12: Effect of the thickness of the pineapple slices on the drying kinetics curve for an air of 65°C

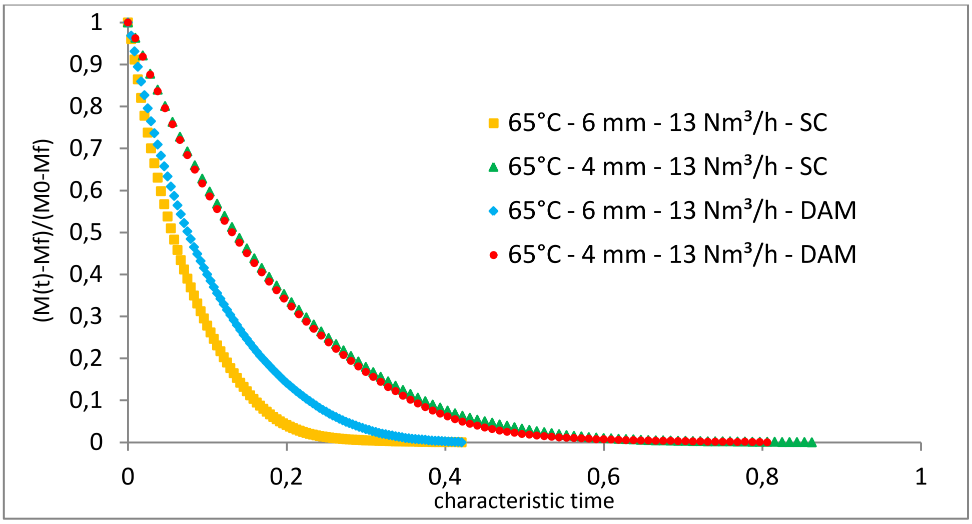

Figure 13: (M(t)-Mf)/(M0-Mf) in function of $(t*D_{eff})/H^2$

Figure 14 presents the effect of different thicknesses on the drying rates for pineapple slices. These curves were obtained by derivation of the moisture content regarding time. No significant effect of the thickness can be observed on the drying rates. However, it can be noticed the presence of a transient initial phase for all the experiments [19]. Indeed, the maximal value for the drying rate J was reached after 5 minutes on average. It implies the presence of an initial transitory phase of drying where the drying rate increases to reach its maximal value. Figure 14 shows that the drying rate varies with the moisture content as expected for internal diffusion [30]. At these experimental conditions, the samples did not show any constant drying rate. A constant drying rate is fully governed by the external diffusion [44]. As there is no plateau noticed for many food materials during the drying operation, it was concluded by some researchers that the most dominant mechanism for water movement was the internal diffusion [28,44]. The absence of a constant rate in these experimental conditions means that the external diffusion was not the limiting rate but it does not mean that it does not have to be taken into account.

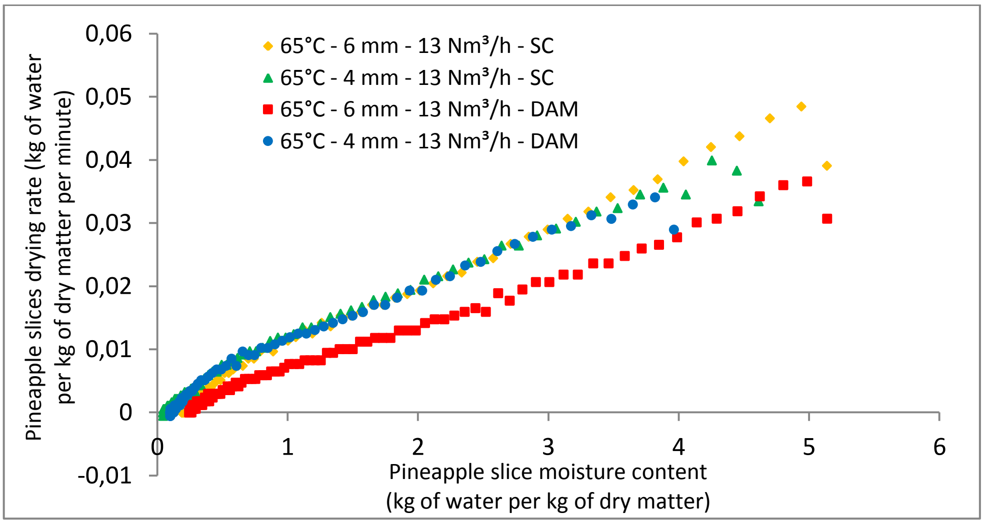

Figure 14: Effect of the pineapple slices thickness on the evolution of the drying rate of the pineapple slices with respect to their moisture content under an air velocity of 13Nm³/h

3.3.3 Influence of the air velocity on the drying curves

In Figure 15, the effect of air velocity on the drying rate becomes obvious. As mentioned for the analysis of the thickness variation, the beginning of the drying suggests to follow a straight line. Moreover, the slope of this straight line is significantly influenced by the air velocity. The slope is more important when the air velocity is equal to 17 Nm³/h in comparison to 13 and 8 Nm³/h. This observation is consistent with the results obtained by S.J Babalis and V.G. Belessiotis for the air velocity study on the drying of figs [50]. This observation suggests that not only the internal resistance should be considered at the beginning of drying but also the external resistance to moisture transfer. It indicates that the evaporation process took place at the interface between the product and the drying medium but this evaporation front decreases progressively towards the inside of the solid which leads the internal moisture diffusion to be predominant [50]. In addition, the drying time required to reach a constant mass is shorter when the air velocity is higher.

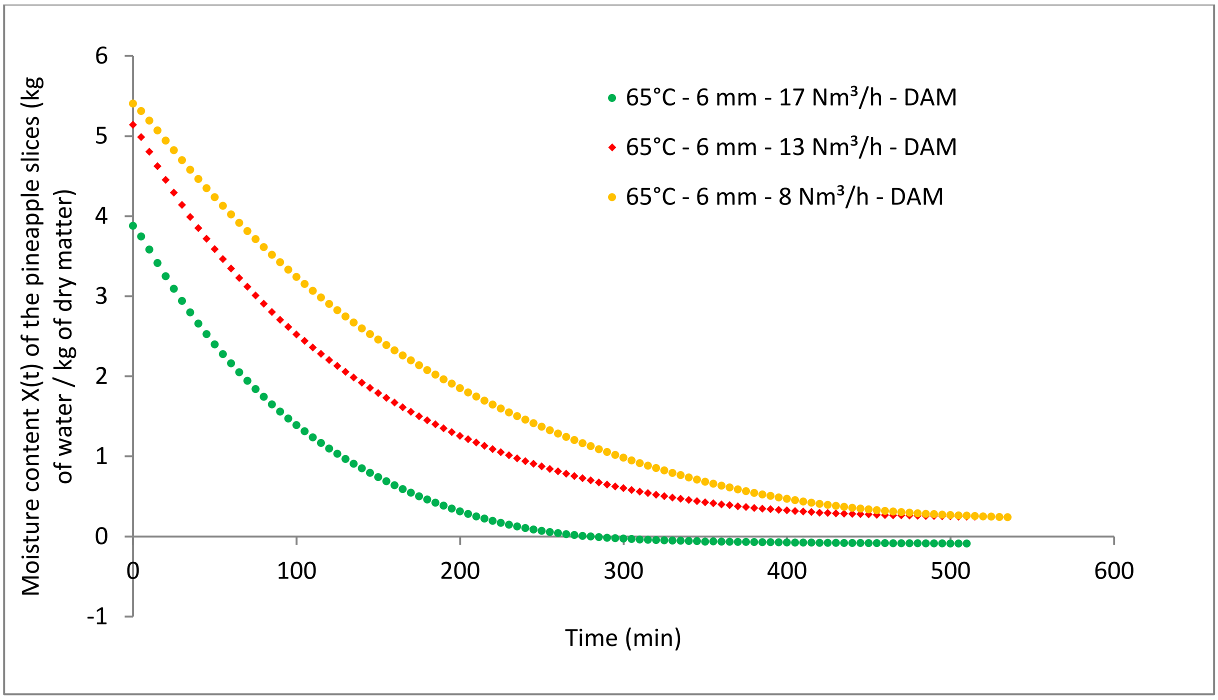

Figure 15: Air velocity effect on the drying curves for an air temperature of 65°C

In Figure 16, the maximum drying rate is reached after a transition phase such as it is observed in Figure 14. Though there is no constant drying rate, the influence of the air velocity on the drying rate can be clearly noticed in Figure 16. For the experiment 4 carried out at 65°C using a airflow rate of 17Nm³/h, the moisture content becomes negative as well as the drying rate for one value of the moisture content (d.b). This can be explained the variability of the moisture content within a pineapple. The moisture content (d.b) is defined in Equation (3-3). If the initial moisture content of the dried pineapple slice in the tunnel dryer was higher than the ones introduced in the oven, it means that X_0 is lower than the real value and then it can lead to a negative value of X(t) if a large amount of water is lost. If $|X_{i+1}(t)| > |X_i(t)|$ then it leads to a negative value of the drying rate as well.

As it was suggested in Figure 14, the drying rate varies with the moisture content; this observation can be noticed on the following graph as well. In addition, the drying rate seems to vary with the moisture content and the air velocity when the moisture content is superior to X=1.5. Whereas, the drying rate suggests that it only depends on the moisture content below X=1.5. This observation is consistent with the observation made in Figure 15. Thus, no constant drying rate does not imply that the external resistance diffusion transfer does not have to be considered as it was suggested by S.V. Jangam [44]. The external resistance is not the limiting rate controlling but it has to be taken into account at the beginning of the experiment. This assumption can be verified by the use of the model presented in 3.4.

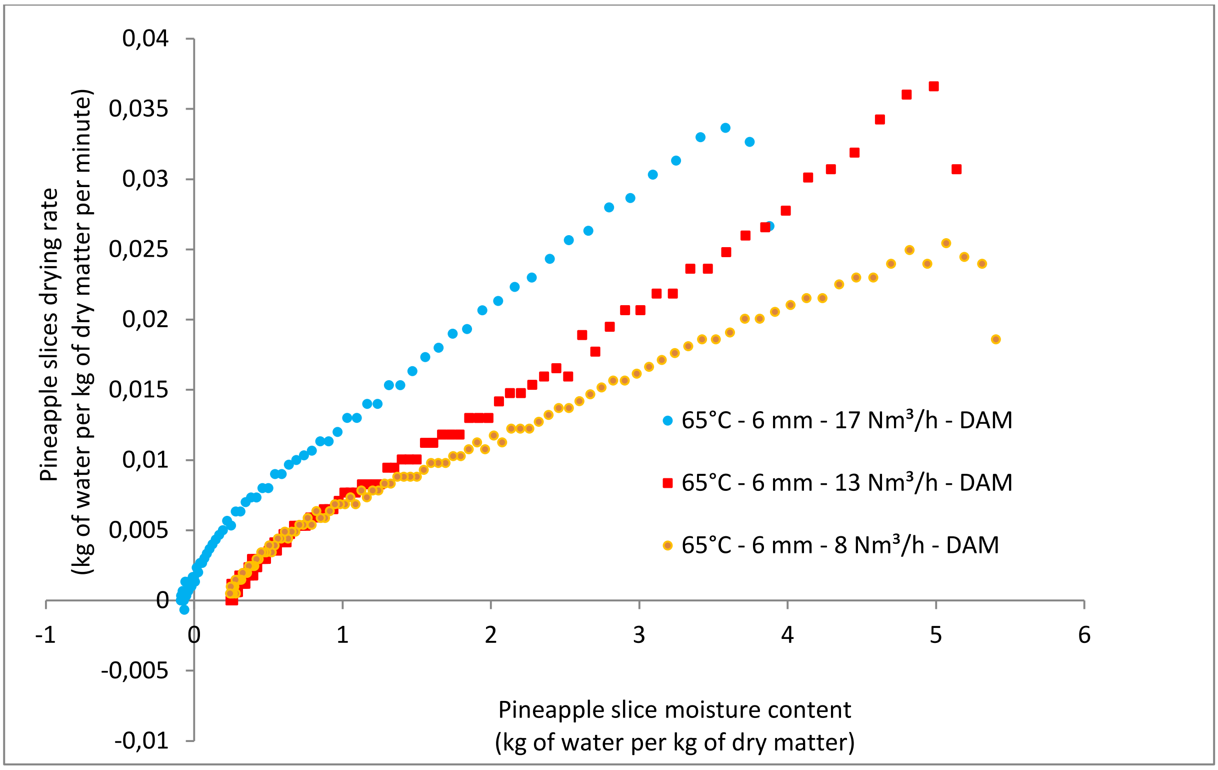

Figure 16: Effect of the air velocity on the evolution of the drying rate of the pineapple slices with respect to their moisture content

The drying rate J can also be used to determine the time needed to decrease the moisture content from X_i to X_f. Actually, it is an analogy of the Levenspiel plot method used to determine the volume of a reactor. An example of this method is presented below. Based on Equation (3-4), Equation (3-5) can be written:

$$\int_{t_i}^{t_f} dt = -\int_{X_i}^{X_f} \frac{dX}{J(X)} \quad (3\text{-}5)$$

This Equation (3-5) means that the area under the curve $1/J(X)$ between X_i and X_f represents the required drying time. Figure 17 Illustrates this method where a zoom is carried out as the values $1/J(X)$ are infinitely high when X is small. Table 6 shows the average time needed to reduce the moisture content during the experiment. For example, this method is applied on the first experiment. This method can be used to have an idea of the required drying time needed to reach a desired moisture content.

Values of moisture contents (X_i to X_f) (dry basis)		$1/J(X_i)$	$1/J(X_f)$	**t (min)**
5	4	31.8	43.2	37.5
4	3	43.2	64.8	54
3	2	64.8	99.4	82.1
2	1	99.4	165.7	132.6
Time from X=5 to X=1				**306.2**

Table 6: Determination of the required drying time for reducing the moisture content

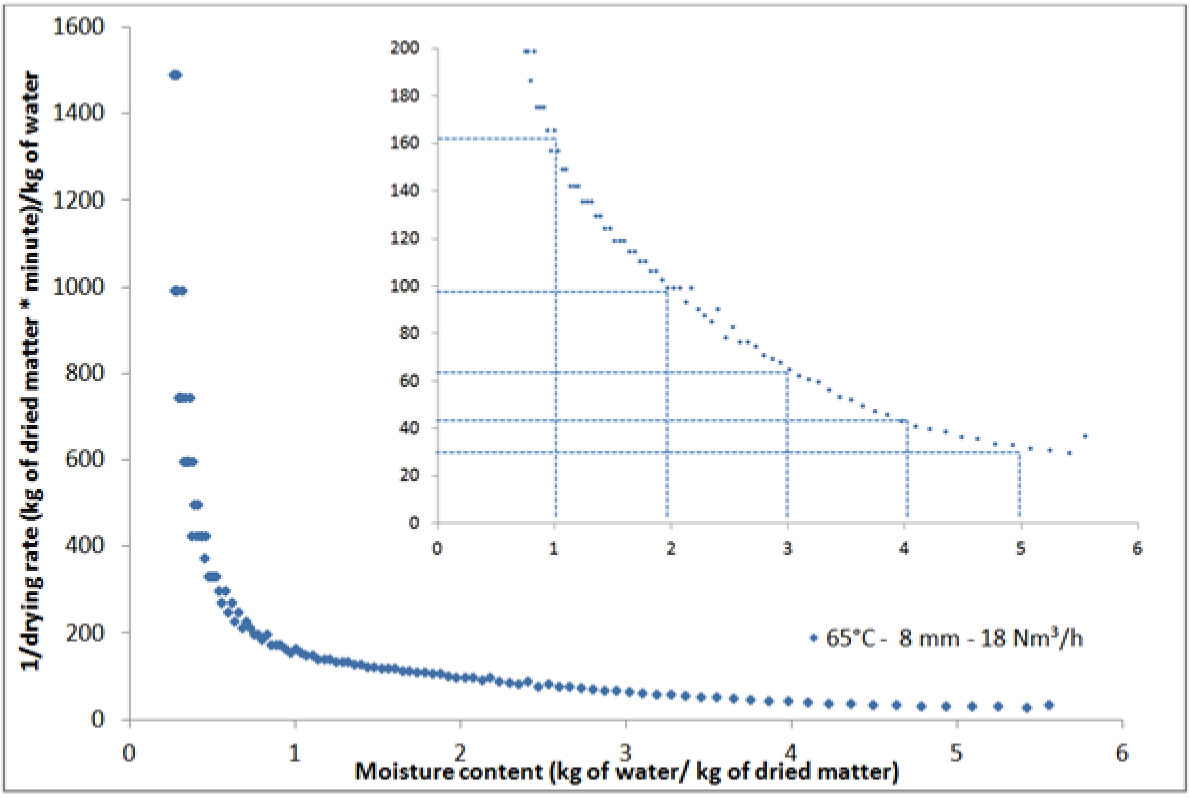

Figure 17: Inverse of the drying rate in function of the moisture content for the first experiment

3.4 Modelling

Based on the experimental results and on the literature, the drying model used in this master thesis to fit the experimental results is based on the Fick's second law of diffusion. The most widely used theoretical drying model to describe food drying has been the Fick's second law of diffusion. According to E. Akpinar, the drying of many food materials could be effectively described by the Fick's second law [28,45]. This section presents a mathematical model of thin layer drying of pineapple slice. Using an analogy with the transient heat conduction [51], the analytical solution of the second Fick's law for an infinite slab was used to calculate the effective diffusion coefficient. This is an effective diffusion coefficient in order to state for a mean value during the drying operation and to allow simple calculations. Information obtained from the experiments is used to develop a mathematical model for the pineapple drying. This model is based on experiments and presents some assumptions. The Fick's Second law solution was implemented in Mathematica© used as software. It provides the value of the effective diffusion coefficient which allows the best fitting with the experimental data according the least squares criterion.

3.4.1 Assumptions

1. The length of the pineapple slice is considered to be infinite. This approximation can be used when the thickness is significantly smaller than the diameter.

2. The morphology and the size of a pineapple size are constant during the whole duration of the drying.

3. Water is considered to be initially distributed homogeneously in a pineapple slice, with an initial concentration written C_0 expressed in kg of water per m³ of pineapple slice.

4. The pineapple slice drying is exclusively limited by transport diffusion phenomena taking place within the product. If it is assumed that local thermodynamic equilibrium is established at the pineapple-air interface, it implies that the temperature and the relative humidity of the air are constant during the drying. Moreover, it means that the water concentration in the inner surface of the pineapple at this interface is constant. This concentration is written C_{eq} and is expressed in kg of water/m³ of pineapple slice.

5. The last assumption is that the water transport taking place inside the pineapple can be modelled by the use of a diffusion equation, involving an effective coefficient diffusion. The effective diffusion coefficient characterises the moisture movement through the product.

3.4.2 Model description

A scheme of the pineapple slice is represented in Figure 18. The Fick's second law equation is described in Equation (3-6) where $C(z,t)$ is the water concentration and is expressed in kg of water per m³ of pineapple slice. Thanks to the symmetry of the system represented in Figure 18, the water concentration depends only on the position in z. $\mathcal{D}_{eff}$ is the effective diffusion coefficient expressed in m² per second. As mentioned previously, the method used to solve the Fick's second law is based on the resolution of conduction heat transfer [51].

$$\frac{\partial C(z,t)}{\partial t} = \mathcal{D}_{eff} \frac{\partial^2 C(z,t)}{\partial z^2} \tag{3-6}$$

There are 3 conditions for the solving of Fick's second law equation of diffusion. There are 2 boundary conditions (Dirichlet homogeneous conditions) and one initial condition. These conditions are respectively expressed in Equations (3-7,8).

$$C(z = H, t > 0) = C(z = 0, t > 0) = C_e \tag{3-7}$$

$$C(0 < z < H, t = 0) = C_0 \tag{3-8}$$

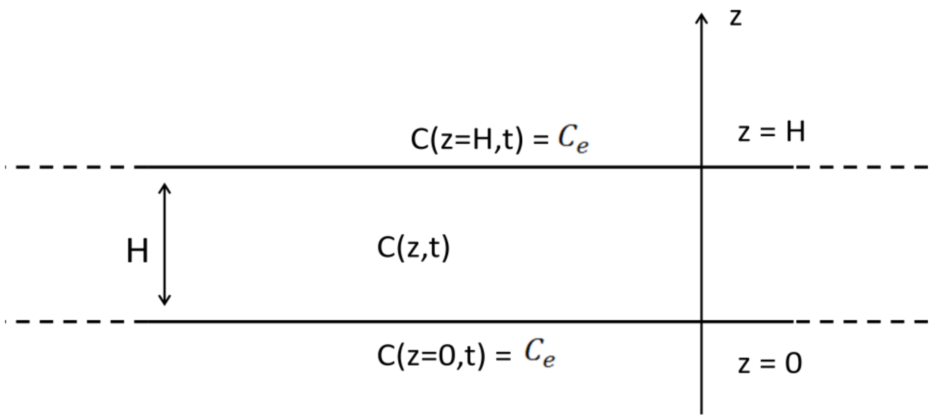

Figure 18: Scheme of a pineapple slice according to the assumption

By writing a new expression for the water concentration as written in Equation (3-9), a dimensionless form of the problem is introduced. Thus, the 2 boundaries conditions and the initial one should be rewritten as well as the Fick's second law. The new system of equations is written with Equations (3-10,11,12).

$$\tilde{C}(z,t) = \frac{C(z,t) - C_{eq}}{C_0 - C_{eq}} \tag{3-9}$$

$$\begin{cases} \tilde{C}(z = H, t > 0) = \tilde{C}(z = 0, t > 0) = 0 & (3\text{-}10) \\ \tilde{C}(0 < z < H, t = 0) = 1 & (3\text{-}11) \\ \dfrac{\partial \tilde{C}(z,t)}{\partial t} = \mathcal{D}_{eff} \dfrac{\partial^2 \tilde{C}(z,t)}{\partial z^2} & (3\text{-}12) \end{cases}$$

In order to solve Equation (3-12), the method of separation of variables needs to be used. The detailed calculation is included in APPENDIX 1.

In order to compare the experimental results to the theoretical ones, the average concentration of water over the spatial coordinate z needs to be calculated. Equation (3-13) is written below. This equation is similar to the equation established by J.K. Sahu for a comparable diffusion problem [52].

$$< \tilde{C} > (t) = \frac{8}{\Pi^2} \sum_{n=1}^{\infty} \frac{1}{(2n-1)^2} e^{-(\mathcal{D}_{eff} \, (\frac{(2n-1)\,\Pi}{H})^2 \, t)} \tag{3-13}$$

The experimental function is defined as $f_{exp}(t)$ and expressed in Equation (3-14). The development followed to determine the theoretical function $f_{theo}(t)$ is presented in APPENDIX 2. The aim of the theoretical function is to reproduce as well as possible the behaviour of the experimental function. The theoretical function is written in Equation (3-15). It implies that the model is suitable if it exists a value of the effective diffusion coefficient $\mathcal{D}_{eff}$ such as $f_{theo}(t)$ is close to $f_{exp}(t)$.

$$f_{exp}(t) = \frac{M(t) - M_d}{M_0 - M_d} \tag{3-14}$$

$$f_{theo}(t) = < \tilde{C} > (t) \tag{3-15}$$

3.4.3 Effective diffusion coefficient identification

In order to discuss the influence of the internal diffusion, the parameter that needs to be identified is the effective diffusion coefficient $\mathcal{D}_{eff}$. In order to estimate this effective coefficient, Mathematica© 7 was used as software. The experimental function and the theoretical function, as written in (3-14) and (3-15) respectively, were entered in the program. As the theoretical function is a sum of an infinite number of terms, 100 terms were considered in the program due to the time required for the calculation. The least squares criterion was used in order to find the best suitable value of the effective diffusion coefficient regarding each experiment. The effective diffusion coefficient value was determined by minimising the sum of the squares difference between the theoretical and the experimental function at each time.

Once the value of the effective diffusion coefficient was evaluated, the sum of square difference was calculated in order to check the reliability of the estimated value. The evaluated value of the effective diffusion coefficient was then introduced in the theoretical function in order to plot the function. As a last step of the method, the difference between the theoretical and experimental function was discussed. Table 7 presents the different values of the effective diffusion coefficient obtained regarding the experiments. These values are coherent with the values found previously in literature. They present the same order of magnitude specifically 10^{-10}m²/s [28,44]. Indeed, the effective diffusion coefficient is in the range of 10^{-11} to 10^{-9} m²/s for food materials [47].

All the graphs obtained with Mathematica© are presented in APPENDIX 3. As the same behaviour between the theoretical and experimental function was identified for all the experiments, only the graphs with the best and the worst fitting are presented in this section. These graphs are presented in Figure 19 and Figure 20 where the points represent the experimental function whereas the continuous line is the theoretical one. It can be noticed that the model has a tendency to under evaluate the experimental results at the beginning of the drying while the opposite behaviour is noticed after a certain time of drying. Indeed, the beginning of the drying experimental curves seems to follow a straight line as it was discussed for Figure 13.

Experiment	Conditions	$\mathcal{D}_{eff}$ (m²/s)	Least Square difference
1	65°C-18Nm³/h-8mm - SC	$5{,}560\ 10^{-10}$	0.28
2	65°C-13Nm³/h-6mm - SC	$5{,}570\ 10^{-10}$	0.23
3	65°C-13Nm³/h-4mm - SC	$2{,}343\ 10^{-10}$	0.28
4	65°C-17Nm³/h-6mm - DAM	$5{,}254\ 10^{-10}$	0.29
5	65°C-13Nm³/h-6mm - DAM	$3{,}997\ 10^{-10}$	0.26
6	65°C-8Nm³/h-6mm - DAM	$3{,}035\ 10^{-10}$	0.53
7	65°C-13Nm³/h-4mm - DAM	$2{,}433\ 10^{-10}$	0.29

Table 7: Estimated effective coefficient values based on the developed model

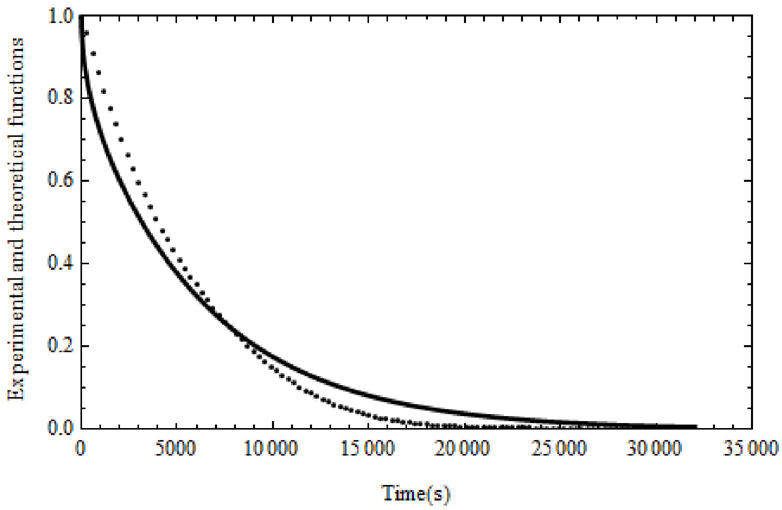

Figure 19: Results obtained with the software Mathematica©.
Experiment 2 – 65°C – 6mm – 13Nm³/h
(. . .) Experimental function (---) Theoretical function.

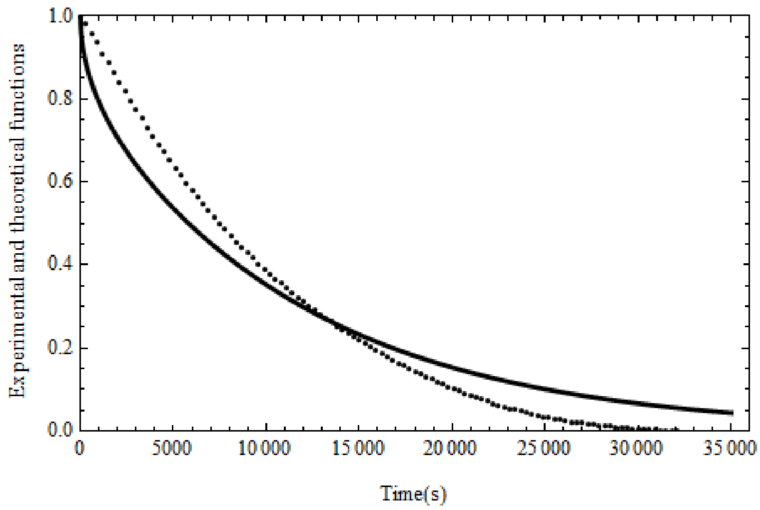

Figure 20: Results obtained with the software Mathematica©.
Experiment 6 – 65°C – 6 mm – 8Nm³/h
(. . .) Experimental function (---) Theoretical function.

3.5 Discussion

The different values of the effective diffusion coefficients are presented in Table 7. The variation of the slice thickness has an influence on the effective diffusion coefficient as reflected by the comparison of experiments 2 with 3 and 5 with 7. As the thickness decreases, the effective diffusion coefficient decreases also. The same observation was found by T.J. Afolabi et al who investigated the thickness of ginger slices [47]. The effective diffusion coefficients obtained for the experiments with the lowest initial thickness were the lowest ones, with respectively $2{,}343\ 10^{-10}$ and $2{,}433\ 10^{-10}$m²/s. If the drying kinetics of the pineapples was independent of the air velocity, the effective diffusion coefficients should have been constant for any air velocity. However, the observation for the air velocity variation is similar to the effect of thickness variation even if the impact on the effective diffusion coefficient seems to be less significant. As the air velocity decreases, the effective diffusion coefficient decreases as well. This observation can be reflected by the following example in which the same variety of pineapples with the same slice thickness is considered. Experiment 5 and 6 present correspondingly an effective diffusion coefficient of $3{,}997\ 10^{-10}$ and $3{,}035\ 10^{-10}$ m²/s at two different air velocities.

The graphs obtained with the mathematical model implemented in Mathematica© are presented in Figure 19 and Figure 20. It can be noticed that the model does not fit perfectly with the experimental data. A more sophisticated kinetic model should be implemented in order to fit entirely with the experimental data. However, the general behaviour of the experimental is quite well reproduced by the theoretical model and only a small deviation is noticed. As mentioned previously, the moisture content at the beginning of the experiment seems to follow a straight line; it can imply that the external transport must be taken into account during the first part of the experiment. The external transport is not the limiting rate controlling step as there is no constant drying rate for the experiments which is characteristic of an external transfer limitation [44]. Though the external transport is not the limiting factor, it does not mean that it does not have to be considered as it was previously explained.

The difference can be explained also by some assumptions that could be too restrictive. It is worth mentioning that the shrinkage of the pineapple slice was not taken into account for the kinetic model. The slice thickness showed a considerable reduction during the drying operation starting from 6 to 3mm. In order to consider the shrinkage, only numerical methods can be used to evaluate the rigorous solution of Fick's law [28]. In this model, the effective diffusion coefficient is considered to be constant during the whole drying operation although the effective diffusion coefficient varies during the drying [53]. This could be another explanation of the reason of the small deviation in the mathematical model. However, some researchers wrote that the decrease of the effective coefficient during the drying operation can be compensated by the shrinkage of the pineapple slice [53].

The drying kinetic model was also established in order to allow a further implementation in the design methodology presented by Pauline Talbot [26]. In order to use properly this design methodology, some assumptions were made. One of them was that the evaporation rate of water is averaged over the drying time. This assumption enables to use the design procedure with basic and limited information about the drying of the desired product [26]. However, an optimisation of the model used during the design procedure will be possible if the kinetics model of pineapple slices drying presented in this section is implemented.

3.6 Conclusion

In this section, the influence of two operating parameters on the drying process and on the effective diffusion coefficient were investigated by performing seven different experiments. These experiments were performed in the laboratory of the TIPs department at the Université libre de Bruxelles. The two investigated parameters were the air velocity and the thickness of the pineapple slice. As expected, the drying time required to reach a constant mass is shorter when the air velocity is higher. Regarding the thickness of the pineapple slice, it was noticed that thinner slices lead to shorter drying times in comparison to thicker slices. This observation is coherent as the thinner the slice is, the smaller the distance is that the moisture needs to travel. In the drying curves, the moisture content $X(t)$ seems to follow a straight line at the beginning of the drying. This analysis suggests that the transport should involve the internal and external resistance at the beginning of the drying as their resistance should have the same order of magnitude. Indeed, on the drying curves of the ratio $\frac{M(t)-M_f}{M_0-M_f}$ in function of $\frac{t\,\mathcal{D}_{eff,ref}}{H^2}$, all the curves are not placed on each other. It suggests that the internal diffusion is not strictly the limited factor of the diffusion.

The air velocity influences the drying rate at the beginning of the drying operation. This observation can be made in Figure 16 where the drying rate varies with the moisture X(t) and with the air velocity up to X=1.5. Below X=1.5, it seems that the drying rate depends mainly on the moisture content which means on the internal diffusion. The variation of the thickness does not show a significant effect on the drying rate curves. It was noticed that the maximum drying rate was reached after 5 minutes on average. Thus, a transition phase is observed at the start of the drying. The moisture content drying curves suggest that an external transport has to be considered at the beginning of the drying. However, there is no constant drying rate. The constant drying rate is typical of external transport limitation. Thus, it is not a limitation by the external transport but both phenomena, internal and external transport need to be considered at the beginning of the drying operation. At this time, the resistances of internal diffusion and external diffusion can have the same order of magnitude.

Based on the experimental results and the Fick's second law of diffusion, a mathematical model was achieved. By using the least square criterion between the experimental data and the theoretical ones, different effective diffusion coefficients could be calculated. The influence of the air velocity and the thickness of the pineapple slice were discussed. As the thickness decreases, the effective diffusion coefficient decreases respectively. The observation for the air velocity was similar but less significant. If the air velocity decreases, the effective diffusion coefficient decreases as well. Thus, the effective diffusion coefficient depends on the air velocity to the contrary of what P.S Madamba related [48]. Although the model does not fit perfectly with the experimental data, it can give a good estimation of the real behaviour of the drying kinetics of the pineapple slices. The deviations can be due to the non inclusion of the external mass transfer at the beginning of the drying and other assumptions which were too restrictive.

As mentioned previously, this mathematical model can be implemented in the model of used in the design methodology proposed by Pauline Talbot [26] in order to provide more accurate results.

CHAPTER 4: ENHANCEMENT OF THE PINEAPPLES DRYING PROCESS AND SUPERVISION OF THE IMPLEMENTATION OF A NEW PROCESSING CENTRE IN UGANDA

4.1 Introduction

This master thesis was performed in partnership with the NGO The Refugee Next Door© (RND). RND© is active in Uganda through different projects. It takes an active part in primary education, vocational training and operational support. These projects are supported with an outlook on self-sustainability and improving people's life [22,23]. Since 2014, RND© has started to support a new socio-economic project in Uganda. This project is the fair trade of dried pineapples. RND© helped to found the Namakwanda Farming Cooperative Program. This program allows to gather local farmers and fruits producers in an agriculture cooperative. RND© has chosen to get involved in an existing organisation by creating a partnership with Fruits Of the Nile (FON©).The partnership aim is to provide a financial and technical help to the dryers' community. Thanks to the fair trade project of dried pineapples, RND© will create employment and promote the women's empowerment [22,23]. In addition, RND© has expected to start exporting the dried pineapples to Belgium soon. Through this project, RND© hopes to become financially independent from the donors to ensure its self sustainability through a reliable income [22,23].

In the framework of this project, RND© started a partnership with the Ecole Polytechnique of the Université libre de Bruxelles in 2015. The goal of this partnership is to improve the drying techniques by enhancing the efficiency and the quality of the drying operation as well as the whole drying process. Two objectives of the present master thesis are presented in this section: the supervision of the implementation of a new processing centre for which the plans were established by the previous volunteers and the investigation on ways of improving the drying process already in place in Uganda. These two tasks were performed in parallel with a third one which is the experimental validation of the design working conditions of the first ventilated solar tunnel dryer built last year and to study the efficiency of this solar dryer. As previously mentioned, the two first missions are presented in this chapter whereas the third one is presented in the next chapter.

4.2 Supervision of the implementation of a new processing centre

4.2.1 Processing centre situation and building construction

RND© wants to alleviate poverty through education and socio-economic projects such as promoting the solar drying process of pineapples [22,23]. The solar drying process is of great interest in Uganda for different reasons: it allows to reduce the post harvest waste, no fuel energy is required and it can be handled by women and old men [19]. Actually, it allows the empowerment of women within the household [20]. In this framework, RND© has chosen to invest in this project by acquiring a land in 2015. This land was acquired to host a school and a new processing centre for the solar pineapple drying. Building a school and a processing centre in Namakwanda town presents 2 major advantages. It will promote the employment of local people and the education for children within the village. In addition, the construction of the 2 buildings on the same field will allow the women to go working while the children follow lessons.

This new processing centre is expected to be a centre of excellence [22]. One of the outcomes of this project is to allow people to work on the quality of the dried products while they become aware of maintaining the required constant quality over time. In the short term, the construction of the processing centre will lead to hire 8 people. Knowing that a family is composed of 10 people on average; it implies that 80 people will indirectly benefit from the introduction of the processing centre including 60% of children [4]. In the long term, more than 100 people will directly or indirectly benefit of this processing centre.

The work regarding the processing centre has started in 2016. The two previous volunteers established the plan of the new processing building. One of the tasks was to supervise the construction of this building by following the plan initially established. The plan was established in such a way that the raw fresh pineapples would never come into contact with the final dried products. Although some adaptations had to be undertaken, the structure of the building was finished at the end of March 2016 as seen in Figure 21.

Figure 21: New processing centre in Namakwanda in March 2016. Building and solar dryers

4.2.3 Dryers construction

The processing centre is composed of a main building where all the operations concerning the preparation of the pineapple slices are performed and solar tunnel dryers. Due to the high quality results regarding the dried pineapples obtained by Mathilde Lhote with the solar dryer built last year, RND© has chosen to trust this new kind of dryer [25]. In January 2016, Mathilde Lhote started to build 3 ventilated solar tunnel dryers on the new acquired land. One of the objectives of this master thesis was to continue building 7 new solar dryers. At the end of March 2016, 8 dryers were completed while only the structure of the 2 last ones was constructed. The 10 dryers could not be finished on schedule due to a lack of money. A picture of the solar dryers in March 2016 is presented in Figure 22.

Figure 22: Solar tunnel dryers in Namakwanda, Uganda in March 2016

In order to facilitate the further construction of the solar tunnel dryers, an instruction manual and a technology factsheet were written. This factsheet was written to summarise the key points of the new implemented solar dryer and to facilitate the understanding of the ventilated solar tunnel drying technology. The instruction manual was written with the help of Mathilde Lhote and Stéphanie Perrini and is presented in APPENDIX 4 whereas the technology factsheet is presented in APPENDIX 5. This manual includes the materials' list with the budget in UGX (1€ = 3778 UGX [54]) and the different steps which need to be followed in order to complete the construction of the ventilated solar tunnel dryer. These dryers are built by using local materials with the help of a local carpenter. Actually, these new dryers need to be built locally in order to ensure ownership and sustainability. The construction of a solar dryer costs 1,483,973 UGX (393€), workforce cost included and takes 5 to 6 days of work. A list of the materials needed to build a dryer is presented in APPENDIX 4. During the construction of the solar tunnel dryers, new ways for improving the robustness of the ventilated solar tunnel dryer could be noticed. These improvements are practical improvements. They are achieved to increase the robustness of the structure as well as the lifetime of the solar dryer itself.

First, bricks were added under each foot of the dryer in order to protect as well as possible the wood from humidity of the ground as presented in Figure 23 a. Additional squares were added to improve the robustness of the structure as seen in Figure 23 a. The way in which the base for the dryer was constructed was not flat, it presented a bump. An adaptation regarding the construction of the dryer base was then proposed in order to ensure a flat surface. The base of the dryer needs to be flat as 4 layers of different materials were placed on each other to ensure a good insulation of the bottom of the dryer. On the top of the dryer, the anti-UV plastic foil was placed to cover the whole dryer. However, the anti-UV plastic foil was directly in contact with the wood. This observation led to a fast spoilage of the plastic foil. Thus, small strips of plastic were then placed on each side and corner of the dryer to avoid any friction as seen in Figure 23 c. It was also noticed that people used to introduce the trays too far inside the dryer which in turn, caused pressure on the plastic foil. In order to avoid this problem, a piece of wood was introduced to block the trays as shown in Figure 23 d. The construction of a solar dryer takes 5 to 6 days of work by the carpenter. Thus, it was suggested to the carpenter to hire an assistant; it reduces the construction time to 3 to 4 days and it creates an additional employment.

Figure 23: Improvements on the solar dryer. (a) Bricks insertion under the feet & added square on the side. (b) Plastic foil to close the dryer during the night. (c) Double layer of plastic foil. (d) Piece of wood introduced on the opposite side of the doors

4.2.4 Starting activities in the processing centre

Even though the construction of the building was late according to the planning, the recruiting process was launched. More than 50 women were interviewed at first. A second round of interviews and practical tests were then organised. The whole drying process was shown to the candidates and they had to be able to reproduce it as well as possible. From this second round of interviews, only 8 women were selected to start working in the new processing centre. In parallel, flowcharts were created. They explain the drying process from the reception of the raw pineapples to the packaging of the dried pineapple slices. An example of process flowchart is illustrated in Figure 43 in APPENDIX 6. These flowcharts were created to be printed as posters and introduced in the new processing building.

4.3 Improvement of the pineapples drying process

4.3.1 Context

RND© has chosen to get involved in an existing company Fruits Of the Nile© (FON). Thus, a pineapple drying process was already in place. The objective of RND© was to start exporting dried organic pineapples to Belgium during this dry season (from January to March). An objective of this master thesis was to improve the quality of the dried pineapples and to ensure the maintenance of the required quality for the Belgian market of dried products over time. Different suggested improvements were proposed by Mathilde Lhote at the end of her master thesis such as keeping constant thickness of the pineapple slices, closing the dryer during the night and the starting work time needs to be earlier [25].

Five farmers of FON© are currently working with RND© for the pineapple drying. They work on 4 different sites which includes around 130 solar cabinet dryers as described in 2.2.1. Although the farmers do not work exclusively with RND©, around 3,000 kg of dried pineapples were produced during the stay in Uganda. The first 1000 kg of dried pineapples were sent to Belgium in the course of March. During the stay in Uganda, the 4 drying sites were visited to establish an overview of the situation. A lot of disparities could be noticed among the different sites; some farmers have available building to work in while others have to work outside. In order to improve the drying process, some actions were undertaken and they are described in the following section.

4.3.2 Improvements of the drying process

Practical improvements were implemented to enhance the quality of the drying process and decrease the waste.

One suggested improvement was the use of a mandolin. Actually, the characteristic time of drying has a magnitude order of $t_c = \frac{H^2}{\mathcal{D}_{eff}}$ where H is the thickness of the pineapple slices and $\mathcal{D}_{eff}$ is the effective diffusion coefficient. This statement suggests that the internal diffusion is mainly responsible of the limitation during the drying process. The characteristic drying time depends on the square of the thickness; thus the thickness is a key parameter of the drying process. If $\mathcal{D}_{eff}$ is taken equal to $5\ 10^{-10}$m²/s as reference value [44], the order of magnitude of the drying process for two different slice thicknesses can be compared in Table 8. A characteristic time of 27.2h is obtained for a slice thickness of 7mm whereas 45h is obtained for 9mm. For a thickness bigger of 2mm, the characteristic time increases of 65%. This observation shows the importance of constant thickness during the drying operation.

Slice thickness H (m)	**Characteristic time, t_c**
0.007	$98{,}000\ s = 27.2\ h$
0.009	$162{,}000\ s = 45\ h$

Table 8: Comparison of the order of magnitude of the drying time for two different slice thicknesses

A closer look was taken on the variability of the pineapple thickness when a mandolin was used or not. An investigation was carried out on 300 pineapple slices when the mandolin was not used while 100 pineapple slices were analysed when the use of the mandolin was implemented. In order to make a comparison, the thicknesses of each pineapple slices were reported. The percentage of the pineapple slices having a certain thickness is presented in Table 9. The measurements were performed with a rule of 0.1 cm of precision. In the case of the use of a mandolin, 75% of the sample had the desired thickness. 100% is not reached because the other 25% was cut with a knife because some pineapples can be too large for using the mandolin. A dispersion of the thickness can be noticed when the mandolin is not used. Although the average is the same (0.7 cm), the standard deviation when the mandolin is not used, is more than 2 times higher than the one when the mandolin is used (s=0.20 & s=0.07).

The use of a mandolin allows to homogenise the drying operation. An instruction sheet on the use of the mandolin was written in order to ensure that the farmers use it in a safe way and that they maintain its cleanliness over time. In order to improve also the homogeneity during the drying operation, it was suggested to rotate the order of the trays within the dryer. At the end of one day of drying, the last tray (put on the side of the exit of air) was put in front position while the first one was put at the last position. Another way to decrease the time of drying and the waste produced during the drying process is to adapt the thickness with the weather conditions. If the weather conditions are good, bigger slice thickness can be cut of 8mm whereas the slice thickness should be cut at 6 or 7mm when the weather is cloudy.

(cm)	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**	**1.0**	**1.1**	**1.2**	**1.3**	**1.4**	**1.5**	**Tot**
No Mandolin (%)	3,0	9,0	17,6	15,9	20,9	15,3	8,6	7,0	1,7	0,3	0,3	0,0	0,3	100
Mandolin (%)	0,0	0,0	1,0	9,0	75,0	10,0	3,0	2,0	0,0	0,0	0,0	0,0	0,0	100

Table 9: Thickness variation with the use (or not) of a mandolin. The thickness was measured by a rule with a precision of 0.1 cm

Another suggested improvement was made regarding working methods. In 2015, the average starting time was 10.20 am [25]. By reorganising the work, starting earlier and introducing an additional person (4 people) and the mandolin, the starting time was 9:20 am on average. This average corresponds to 8 recordings of the starting drying time on the first day of drying. Although there is an improvement, the starting time can still be earlier. Advice regarding hygiene and maintenance of the devices such as dryers was also provided in order to help them with the preservation of a high quality production. For some drying sites, a working house to prepare the pineapple slices is required to avoid dust, flags and insect. The importance of the cleanliness of the working site was mentioned few times.

As the drying operation takes more than 1 day, an additional piece of plastic was added on the open sides of the dryer to close them during the night as suggested by Mathilde Lhote [25]. This adjustment was performed to prevent an overly high humidity within the dryer and avoid a phenomenon of rehydration of the pineapple slices if the air is saturated in water. A closer look to the humidity within the dryer is taken in the next chapter. Another proposal was to insert a mosquito net in front of the opening created by the fans. It can prevent flags and big dust particles to enter within the ventilated solar tunnel dryer.

Regarding team management, monthly meetings between the farmers were established. It was noticed that the farmers did not communicate with each other. The communication is essential between them as they can share their experience regarding the drying process such as improvement or encountered problems. Thanks to these meetings, some logistic problems could be solved and infrastructure problems could be raised. The farmers became aware of the importance of the cleanliness and the maintenance of the dryers. Through these meetings, farmers can take ownership of the actions that need to be carried out.

FON© and RND© kept initially only a first quality of dried pineapples. In order to reduce the waste, it was decided to define two qualities of dried pineapples: the premium and the ordinary quality. Obviously, two different prices are applied but it allows to reduce the rejects when the dried pineapples are sorted and it allows to increase the incomes of the farmers.

Although farmers sell some peels for the livestock food, a great part of the waste is still present on the drying site. This waste is responsible for the presence of insects and animals. The compost of the peel was proposed to be used as a fertilizer for crops as the raw pineapples were organic. The compost needs to be realised far from the dryers and the place where the fresh pineapples are processed.

4.4 Conclusion

During the stay in Uganda, different tasks were performed. Among these different missions, the supervision of the new processing centre and the improvement of the pineapple drying process are detailed.

Despite some adjustments that had to be undertaken, the construction of the new processing still managed to go forward. The structure of the building was finished and 8 solar dryers were completed. An instruction manual and a technology factsheet were written in order to facilitate the understanding of the building of ventilated solar tunnel dryers and its technology key parameters. The recruiting process was achieved to find local people interested to work in the new processing centre. The establishment of the flowcharts allows to explain the drying process from the reception of the raw pineapples to the packaging of the dried pineapple slices. Although the candidates could follow a training regarding the pineapples drying process during their second round of interviews, further trainings need to organise. The required devices to process the raw pineapples still need to be bought for the processing centre.

In terms of improvement of the drying process, a mandolin was introduced to ensure that the pineapple slices have a constant thickness. Thus, it allows to improve the homogeneity of the pineapples drying. The quality of the drying was also improved by the introduction of plastic foil on the open sides to limit the moisture within the dryer during the night or bad weather. A reorganisation of the work and a better definition of the tasks allowed to start the drying operation earlier though further improvements can still lead to start earlier. Farmers became aware of the importance of keeping a constant high quality standard. General advice regarding cleanliness and maintenance were provided during the monthly meetings in order to allow the farmer to take ownership of the different suggested improvements. The definitions of the two grades of quality will decrease the rejects and improve the farmers' incomes.

Although some suggested improvements could be implemented, there are still different ways to investigate in order to continue the enhancement of the pineapples drying process. Some farmers need to deal with a lack of infrastructure. They need to build a working house to prevent dust and flags to be in contact with the pineapple slices or be at least working on a table. The waste treatment still needs to be investigated in order to provide a reliable source of disposal.

CHAPTER 5: EXPERIMENTS ON THE SOLAR TUNNEL DRYER IN UGANDA

5.1 Introduction

In the framework of this master thesis, experiments were performed on the ventilated solar tunnel dryer implemented in Uganda last year by Mathilde Lhote [25]. Actually, the harvest of the pineapples ends at the end of March and the rainy season starts in April. Thus, the experiments were achieved from February to March. Some experiments were carried out to know the mass of dried pineapples that was obtained from the raw pineapples. Other experiments were performed to investigate the humidity and the temperature of the air within the ventilated solar tunnel dryer as well as outside of the dryer. During this two months period, 7 complete drying operations were followed. Four drying operations occurred in 2 days whereas the three others took place in 3 days.

These experiments were performed to validate experimentally the three design conditions used in the design methodology established by Pauline Talbot [26]. The three conditions are listed previously in 1.1.6. In order to ensure a homogeneous and efficient drying, these conditions need to be fulfilled. In other words, if these conditions are respected, the drying product will be in contact with an air at a specified temperature and far from being saturated with water [26]. The experiments regarding the comparison between the mass of the raw pineapples and the final dried products were requested by the NGO RND©. Based on the energy balance equations presented in 2.3.2, the efficiency of the dryer is discussed in this chapter.

In order to fulfil these tasks, different parameters were measured during the drying operation. The temperature and the relative humidity within the dryer were measured at the end of the heating part and at the end of the drying part. Climatic data such as ambient temperature, relative humidity and the global solar radiation which is the sum of direct solar radiation and diffuse solar radiation, was measured [55].

In this chapter, the materials and methods used in Uganda are presented. Then, the comparison between the mass of the raw pineapples and the dried pineapples is discussed. After, an analysis of the three expected design conditions is performed. The efficiency of the dryer is discussed and to conclude, a discussion about the obtained results is presented.

5.2 Materials and methods

For the weight measurement, two different scales were used. In order to weight the raw fresh pineapples, a scale from Uganda was used. Its accuracy is $\pm$0,5kg. This scale is composed of a pointed large "S" hook which allows to hang the product to weight it. The scale used to weight the pineapple slices is an electronic kitchen scale SALTER©. Its range of use is 0 to 5000g with an accuracy of $\pm$1g. It is important to notice that mass measurements could not be performed with a high accuracy. Indeed, the children and even the adults ate some pineapples during the drying to check if they were ready. Unfortunately, this error cannot be quantified.

The solarimeter KIMO© SL100 was used to measure the global solar radiation (F_S) with an accuracy better than 0.5 W/m². The solarimeter was left on the top of a dryer to take the measurement. The thermometer TFA© used for temperature measurement has an accuracy of $\pm$1°C for a range of temperature of -20°C to 100°C. The probes Geo Fennel FHT 70 Datalog used to measure the relative humidity and the temperature have an accuracy of $\pm$1°C for the temperature and $\pm$3% for the relative humidity. These probes or the thermometer were arranged at 3 different places according to the experiments:

- outside of the dryer in the shadow to measure the ambient temperature (T_{amb}) and relative humidity of the ambient air (RH_{amb}),
- inside the dryer, between the heating zone and the dry zone to measure the air temperature at the end of the heating zone ($T_{air,heat}$) and to measure the relative humidity (RH_{heat}),
- inside the dryer at the end of the dry zone to measure the air temperature at the end of the dry zone ($T_{air,dry}$) and to measure the relative humidity (RH_{dry}).

The probes were placed in a way to avoid that the evaporation of the water from the pineapple does not cheat the measurements. They were scheduled to take the measurement every 5 minutes for all the experiments except the two last experiments (every minute) whereas the other measurements were taken every 20 minutes.

The drying day started around 7.00 am. One or two people were responsible for the pineapple peeling, another one for the slice cutting and a last one for the removing of the heart, the centre of the pineapple slices. The farmer used to employ two other people, sometimes three to help him to perform all the processing tasks. When the slices are ready, they are weighted, laid on the trays and inserted within the dryer. At the end of the day, if the conditions were suitable, the pineapple slices were weighted to evaluate the evaporated mass of water. Then, the pineapples slices are inserted back in the dryer if required.

5.3 Results and discussion

5.3.1 Mass pineapple analysis

RND© requested to investigate the mass of dried pineapples in comparison to the raw fresh fruits mass. The results of this investigation are presented in Table 10. First, the mass of the raw pineapples was weighted. After being processed, the pineapples slices were weighted. They were weighted before being introduced on the trays. At the end of the drying the mass of dried pineapple slices was characterised. Finally, the leftover dried pineapple slices were weighted after being sorted.

Experiment	Mass fresh pineapples (g)	Mass of pineapple slices (g)	Mass of dried pineapple slices (g)	Ratio of dried pineapples on fresh pineapples	Ratio of dried pineapples on pineapple slices
1		31453 ± 16	5841 ± 3		0,19
2		21365 ± 8	3530 ± 3		0,17
3	1842 ± 1	630 ± 1	107 ± 1	0,06	0,17
4	5296 ± 3	1729 ± 1	259 ± 1	0,05	0,15
5	46000 ± 1000	16967 ±10	2927 ± 3	0,06	0,17
6		27629 ± 13	4608 ± 3		0,17
7		23357 ± 11	3825 ± 3		0,16
8		23347 ± 11	4559 ± 3		0,20
9		28428 ± 9	4535 ± 3		0,16
10	62000 ± 1000	19325 ± 10	2977 ± 3	0,05	0,15
11	53000 ± 1000	18491 ±10	2941 ± 3	0,06	0,16
12	60000 ± 1000	22314 ± 10	3243 ± 3	0,05	0,15

Table 10: Comparison of the pineapple mass between the raw fresh pineapples and the dried pineapple slices

It is noticed that around 5 % of the fresh pineapple mass corresponds to the obtained dried pineapple mass. Once the dried pineapples slices were obtained, they were sorted. From this sorting step, an average of 76% of dried pineapples is considered as a good one whereas the leftover is considered as reject. From this table, it can be noticed that the average filling is 23,268kg if the convenient experiments are considered. According to the design methodology, the suggested amount of fresh pineapple slices that can be introduced in the dryer is 30kg of fresh pineapple slices [25]. However, the farmers preferred to lower the amount of introduced fresh pineapple slices due to the unpredictable weather conditions of this year. It is worth mentioning to underline that the errors inserted in Table 10 do not take into account the pineapple slices that could be eaten during the drying process. This error cannot be quantified. Based on these results and on the use of the dryer as its maximum capability, it can be assumed that around 86kg of raw fresh pineapples are needed to give 30 kg of fresh pineapple slices. This observation highlights the importance of waste treatment. After two or three days of drying, 5.1 kg of dried pineapple slices could be obtained on average. Then, the farmers use to keep 76% of dried pineapple slices, which means 3.9 kg of good dried products at the end of the drying process.

5.3.2 Humidity analysis

The relative humidity of the air was measured within the dryer at the end of the heating zone and at the end of the drying zone. It was also measured for the ambient air. These results are presented in Table 17, Table 18 and Table 19 in APPENDIX 7. Table 17 presents the results obtained for the first day of drying while Table 18 and Table 19 present respectively the results obtained for the second and third day if required. It can be noticed that during all the experiments the average relative humidity remained far from 100 %. If the weather conditions were good, the average relative humidity remained below 20% of relative humidity whereas the average relative humidity could reach around 45% when it was a rainy day as it was the case for the day 1 of experiment 2 and for the day 2 of experiment 1 for example.

In Figure 24 and Figure 25, the relative humidity and the temperature over time are presented. The temperature analysis is performed in the next subsection. The temperatures are represented in Figure 24 and Figure 25 to be reliable because the relative moisture depends on the temperature (Equation (5-1)). In Figure 24, the relative humidity is far below 100% during the two days of drying as expected. The same observation can be done for both relative humidity in Figure 25. In Figure 24, another observation is that the relative humidity never reached 100% during the night. It means that the phenomena of condensation could be avoided. In order to verify this assumption during the experiments, the mass of the pineapple slices was weighted on the evening and on the morning of the next day. The mass weighted on the morning of the following day was never higher than the mass weighted the day evening before. The experiment in Figure 25 started at 11.40 am because of bad weather conditions on the morning. Thus, the farmers decided to wait until the weather conditions became favourable.

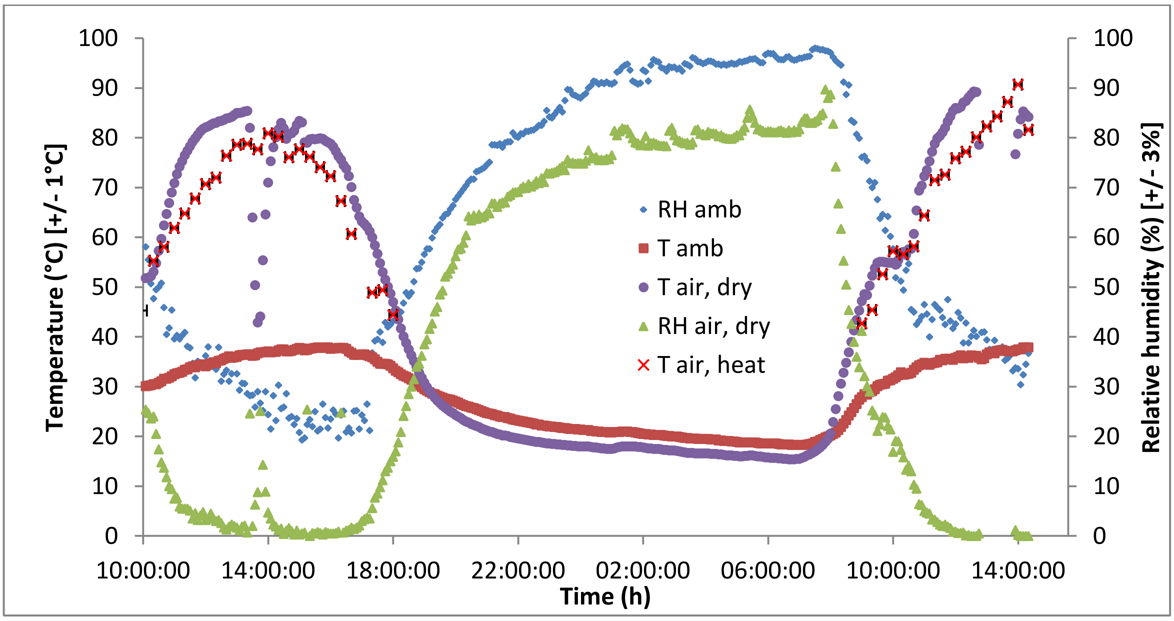

Figure 24: Temperature and relative moisture evolution within the dryer at the end of the dry zone and outside of the dryer. Test 5 (15-03 & 16-03)

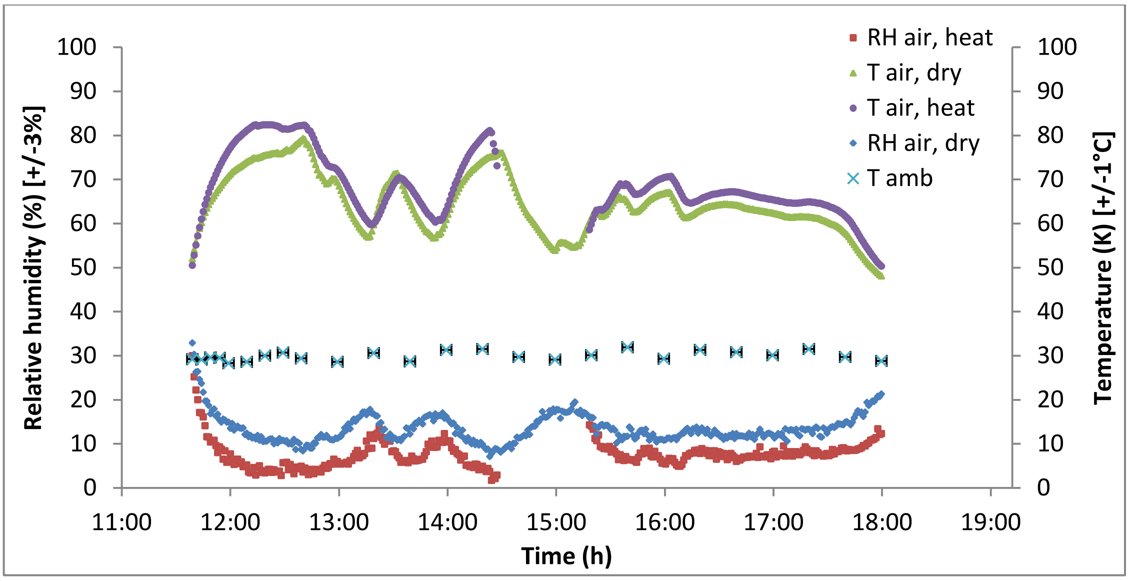

Figure 25: Temperature and relative moisture evolution within the dryer at the end of the dry zone and outside of the dryer. Test 8 (day1, 18-03)

The error bars represented in Figure 24 and Figure 25 show the incertitude linked to the time when the measurements were taken. They were taken every 20 minutes but an incertitude of $\pm$1min can be taken as confidence interval. The error bars related to the measurement errors are not represented to clarify the chart. The error on the relative humidity is $\pm$3% whereas the error on the temperature measurement is $\pm$1°C.

The observation related to the relative humidity proved that the airflow chosen during the design methodology was convenient. In order to ensure that the humidity is far from the saturation with water, the absolute humidity can be used. Actually, the absolute humidity Y does not depend on the temperature and can be calculated from the relative humidity thanks to Equations (5-1,2) where M_w and M_a are the molar mass of water and air respectively [29,56]. p_{tot} is the total pressure and the partial pressure of water (p_w) is calculated thanks to the relative humidity and the saturation pressure of water at temperature T. This saturation pressure $p_{sat}(T)$ can be calculated with the Clausius-Clapeyron law [29].

$$Y = \frac{M_w}{M_a} \frac{p_w}{(p_{tot} - p_w)} \tag{5-1}$$

$$p_w = RH\, p_{sat}(T) \tag{5-2}$$

The absolute humidity Y for each experiment is presented in Table 11. They are expressed in kg of water per kg of dry air and they are based on the average value of the relative humidity and temperature. The total pressure in Jinja (Uganda) for February and March was 1011 hPa [57]. The saturated absolute humidity at a temperature of 60°C and 70°C are respectively Y=0.152$\mathrm{kg_{water}/kg_{dry\ air}}$ and Y=0.277$\mathrm{kg_{water}/kg_{dry\ air}}$. In comparison with the values of absolute humidity obtained for the air at the end of the heating zone and at the end of the dry zone, it can be concluded that the absolute humidity is far below the saturation value.

On average, the absolute humidity $Y_{air,dry}$ presents a value higher than the ambient absolute humidity. It suggests that the vapour released from the water evaporation was carried away with the airflow. For the experiment 3 and 4, it is noticed that the absolute humidity at the end of the heating zone is higher than the absolute humidity of the ambient air. This observation can be explained by a local phenomenon of recirculation air conditions due to natural convection within the dryer or an arrangement of the probes too close from the drying pineapple slices. This observation was also noticed by Mathilde Lhote [25]. Nevertheless, all the values are quite close to each other and remain far below the saturation concentration; it suggests that the air is sufficiently renewed to ensure good drying conditions.

		Test 1	**Test 2**	**Test 3**	**Test 4**	**Test 5**	**Test 6**	**Test 7**	**Test 8**	**Test 9**
Day 1	Y_{amb}	0,0103	0,0168		0,0136	0,0173	0,0151	0,0123		0,0160
	$Y_{air,heat}$				0,0141				0,0144	
	$Y_{air,dry}$	0,0117	0,0194			0,0157	0,0189	0,0143	0,0213	0,0252
Day 2	Y_{amb}	0,0160	0,0170	0,0151	0,0143	0,0163	0,0173	0,0162		0,0163
	$Y_{air,heat}$			0,0194	0,0208				0,0233	
	$Y_{air,dry}$	0,0172	0,0172			0,0251		0,0216	0,0268	0,0188
Day 3	Y_{amb}	0,0144	0,0183							0,0167
	$Y_{air,heat}$									
	$Y_{air,dry}$	0,0148	0,0212							0,0165

Table 11: Absolute humidity of the air inside and outside of the dryer for each experiment

5.3.3 Temperature analysis

The two other design specifications that need to be verified are the followings. The average temperature of the air at the end of the heating zone should reach a specific value depending on the product to dry and the average temperature at the end of the drying zone should reach a specific value as well. These values should be included between 70-75°C for the pineapple drying in Uganda [26]. All the average temperature values are expressed in degree C with an accuracy of $\pm$1°C. They are presented in Table 12. The temperatures of the air at the end of the heating and at the end of the drying zone were close to each other for almost all the drying experiments.

In Figure 24 and Figure 25, it can also be noticed that the temperatures within the dryer ($T_{air,dry}$ and $T_{air,heat}$) are 30°C higher than the ambient temperature. The two temperatures within the dryer were close to each other during the whole drying operation. This observation allows to confirm two design specifications formulated by Pauline Talbot to guarantee good conditions of drying [26]. The drop of the air temperature at the end of the drying zone in Figure 24 around 2pm can be explained by the removing of the device. Actually, if the temperature was too high within the solar dryer, the electronic probe device could be damaged. The drying presented in Figure 24 could be performed in less than two days whereas the other drying experiment presented in Figure 25 could be performed in two days.

		Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9
Day 1	T_{amb}	33	28		33	27	34	35	30	31
	$T_{air,heat}$	57	43		65	42	60	66	68	53
	$T_{air,dry}$	50	39			44	69	71	64	55
Day 2	T_{amb}	28	32	31	33	32	32	34	31	33
	$T_{air,heat}$	43	55	62	67	59	64	69	63	56
	$T_{air,dry}$	36	58			66		72	60	63
Day 3	T_{amb}	34	33							32
	$T_{air,heat}$	67	64							60
	$T_{air,dry}$	51	61							66

Table 12: Average temperatures of the air at the end of the heating zone, the draying zone and of the ambient air

Though the temperatures of the air at the end of the heating zone $T_{air,heat}$ and the drying zone $T_{air,dry}$ were close to each other, their average values are below the requested drying temperature of 70-75°C [26]. Actually, the average temperatures are equal to $T_{air,dry}^{average}$=58°C and $T_{air,heat}^{average}$=60°C if all the experiments are considered. If only the days with favourable weather conditions are considered, the average of both temperatures climbs to $T_{air,dry}^{average}$=$T_{air,heat}^{average}$=64°C. These lower values of average temperature can be explained by the drying measurement time which continued up to 6 pm whereas it was considered to last up to 4 pm in the design methodology [25,26]. In addition, the data used in the design methodology are theoretical data used a priori whereas the data used in this master thesis are experimental data. However, temperature values included between 80 and 90°C could be observed for the air temperature at the end of the drying at some moment during the day. When the weather conditions were favourable, a temperature $T_{air,dry}$ higher than 70°C can be reached for at least 3h such as it was the case for the test 7, the 15th and 16th of March as well as for the test of the 11th of March. On the 15th and 16th of March, the average temperatures of the air of the heating and drying zone could be 70°C on average which is the required expected drying temperature. It was also noticed that the temperature of the air at the end of the drying zone was higher than the one at the middle of the dryer as shown in Figure 26. It can be justified by the emplacement of the thermometer. Actually, the thermometer could not be arranged completely inside of the dryer as it was achieved for the electronic probes. Thus, the measured temperature could be lower than the one in the centre of the dryer. Nevertheless, the temperature maintained a higher value than 70°C from 11am to 4.30 pm in Figure 26. Thus, it was concluded that the drying products underwent a sufficiently high temperature to be dried correctly. This observation was also noticed by Mathilde Lhote in her master thesis [25].

When the weather conditions were not good, more than 2 days were needed to perform the drying operation. Test 1 on the 11, 12 and 13 of February, the temperature never reached 70°C within the dryer. The same observation can be achieved for the second test on the 21, 22 and 23 of February; a temperature higher than 70°C was achieved on the last day of drying only. Thus, it reminds the importance of the good weather conditions in order to ensure an efficient drying operation, especially the global solar radiation flux.

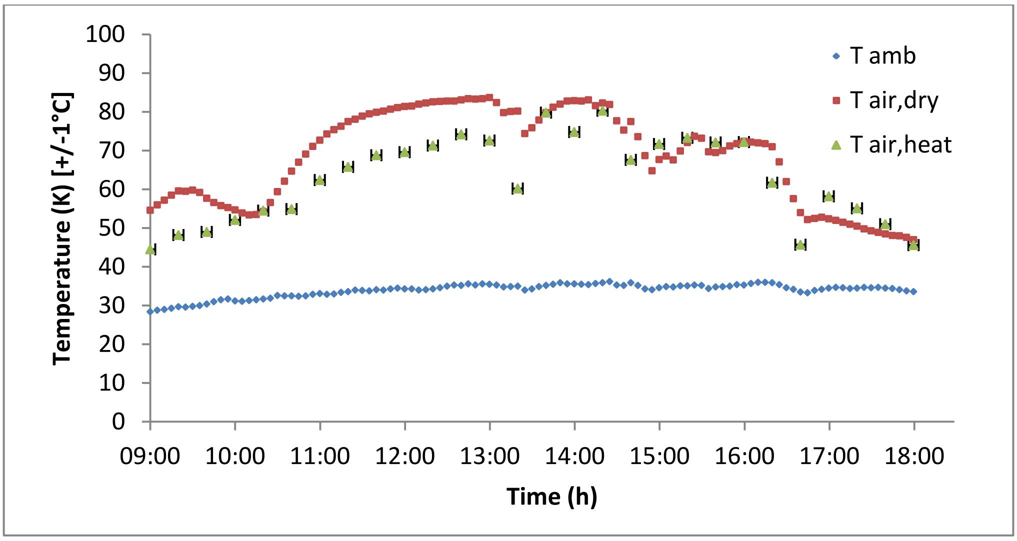

Figure 26: Temperature evolution for the test 6 performed on the 11 of March

5.3.4 Efficiency of the solar tunnel dryer

An attempt to define the overall efficiency of the solar tunnel dryer is presented in this section. In order to calculate the overall efficiency of the dryer, global balance equations need to be solved. These equations are based on the energy balance equations presented in 2.3.2 of this master thesis. The efficiency of the solar tunnel dryer η_{std} is estimated as written in Equation (5-3) where E_u is the energy consumed to evaporate the water and to heat up the air whereas E_{solar} is the energy captured from the sun by the solar tunnel dryer.

$$\eta_{std} = \frac{E_u}{E_{solar}} 100 \tag{5-3}$$

The two energies used in the Equation (5-3) are calculated in Equation (5-4) and (5-5).

$$E_u = m_{water,evap}\mathcal{L}_w + \int_0^{t_d} A_{nom,air}\, \rho_a c_{p,a}(T_{air,dry} - T_{amb})dt \tag{5-4}$$

$$E_{solar} = \xi \int_0^{t_d} (F_S + F_{IR,atm})dt \tag{5-5}$$

ξ is the ground surface of the solar tunnel dryer. F_S is the global solar radiation measured with the solarimeter and $F_{IR,atm}$ is the atmospheric infrared radiation flux estimated by Equation (5-6). ε_{sky} is the sky emissivity and T_{sky} is the sky temperature; they both depend on the dew point temperature T_{dp}. The dew point temperature is the temperature at which the partial pressure of water is equal to the saturated pressure of water [58]. σ is the Stefan-Boltzmann constant.

$$F_{IR,atm} = \varepsilon_{sky}\sigma T_{sky}^4 \tag{5-6}$$

Thanks to these three equations, an estimated value of the efficiency can be calculated for each day of each experiment as well as the overall efficiency for the whole drying process. First, ε_{sky} and T_{sky} need to be calculated thanks to Equations (5-7) and (5-8) [37,59]. The dew point temperature appearing within the equations can be estimated by the Heinrich Gustav Magnus-Tetens Formula [58] as the validity domain is respected. This formula is written in Equation (5-9) where T is expressed in °C and RH in %.It is actually a function of the temperature and the relative humidity. In order to solve Equation (5-8), it is considered that t=12, which is the number of hours past midnight [25,37]. In Equation (5-8), T_{sky} and T_{amb} are expressed in degree K whereas T_{dp} is in degree°C.

$$\varepsilon_{sky} = 0.787 + 0.764 \ln \left(\frac{T_{dp}}{273.15}\right) \tag{5-7}$$

$$T_{sky} = T_{amb} \left[0.711 + 0.0056\, T_{dp} + 7.3\, 10^{-5} T_{dp}^{2} + 0.013 \cos\left(\frac{2\Pi t}{24}\right)\right]^{1/4} \tag{5-8}$$

$$T_{dp} = \frac{b\left(\frac{a\,T}{b+T} + \ln\left(\frac{RH}{100}\right)\right)}{a - \left(\frac{a\,T}{b+T} + \ln\left(\frac{RH}{100}\right)\right)} \quad with \begin{cases} a = 17.27°C \\ b = 237.7°C \end{cases} \tag{5-9}$$

The obtained results of T_{dp}, ε_{sky}, T_{sky} and $F_{IR,atm}$ for the resolution of Equations (5-6) to (5-9) are presented in APPENDIX 8. F_S is also presented in APPENDIX 7. The F_S values correspond to the experimental values obtained on the field.

The data necessary to solve Equations (5-4) and (5-5) are presented in Table 13 and in APPENDIX 7. Then, it was possible to estimate an efficiency of the solar tunnel dryer as written in (5-3). The detailed efficiency for each day is presented in APPENDIX 7 whereas the overall efficiency for the whole drying process is expressed in Table 14.

Symbol	Value and units
$\boldsymbol{\sigma}$	$5.6703\ 10^{-8} \frac{J}{K^4 m^2 s}$
$\boldsymbol{\xi}$	$14.235\ m^2$
$\boldsymbol{A_{nom,air}}$	$0.024 \frac{m^3}{s}$
$\boldsymbol{\rho_a(60°C)}$	$1.067\ \frac{kg}{m^3}$
$\boldsymbol{c_{p,a}\ (60°C)}$	$1009 \frac{J}{kg\ K}$
$\boldsymbol{\mathcal{L}_w(60°C)}$	$2358.4\ \frac{kJ}{kg}$

Table 13: Fixed parameters used for the calculation of the solar tunnel dryer efficiency [60,61,62]

The overall efficiency of the solar tunnel dryer is estimated at 9% on average. This efficiency is low but it was expected as the only energy source is the solar energy. As a comparison, the average efficiency of solar panel is between 11 and 15% [63]. The definition of the efficiency suggests that the efficiency is higher when a high mass of water is evaporated. This observation can be noticed by investigate the difference in efficiency between the two or three days of drying. As expected, the efficiency value is generally higher for the first day, 13% for the first day of experiment 1 while it drops down for the third day around 4 %. For example, the farmers should wash the solar dryer every two days to remove the accumulated dust on the plastic foil in order to improve this efficiency.

	Drying 1	Drying 2	Drying 5	Drying 7	Drying 9	Average
E_u (MJ)	90	84	80	86	103	**88**
E_{solar} (MJ)	1210	977	825	862	1018	**978**
η_{std} (%)	7	9	10	10	10	**9**

Table 14: Overall estimated efficiency for the whole drying process

5.4 Conclusion

In this chapter, the results of the experiments performed in Uganda are presented. The investigation of the obtained results allows to analyse the efficiency of the solar tunnel dryer. First, an analysis of the pineapple mass is performed. As requested by RND©, the comparison between the mass of the dried pineapples and the raw fresh pineapples is achieved. If the dryer is used at its maximum capability, around 86kg of raw pineapples are required to fulfil the dryer with 30kg of fresh pineapple slices. After the drying operation, 5.1kg of dried pineapples are obtained whose 3.9kg are kept after sorting.

Some experiments were carried out on site to validate experimentally the design specifications stated in 1.1.6. These design specification are used to ensure an efficient and homogeneous drying operation. During the drying operation, the relative humidity remained far below 100% as requested. Even during the night, the relative humidity did not reach 100% for the performed experimental tests. The analysis of the absolute humidity highlighted that a phenomenon of recirculation of air could take place within the solar dryer or the probes could be arranged too close of the pineapple slices during the drying. Indeed, the absolute humidity of the air at the end of the heating zone was higher than the one of the ambient air. Nevertheless, the absolute humidity remained far below the saturation value. The temperature of the air at the end of the heating zone and the drying zone were close to each other though these temperatures were lowered than the expected 70-75°C [25,26]. However, the temperatures reached within the dryer were higher than 70°C for a period of time depending on the weather conditions which is considered to be sufficient to ensure good drying conditions.

An attempt to estimate the efficiency of the solar tunnel dryer is achieved in this chapter. Based on the energy balances defined in 2.3.2, an overall efficiency can be defined. The efficiency of the solar tunnel dryer can be calculated thanks to the experimental data obtained from the field. The average efficiency of the solar tunnel dryer is 9% which seems to be low. Due to its definition, the efficiency is higher during the first day of drying whereas it drops down for the following day as the evaporated mass of water decreases.

CHAPTER 6: CONCLUSIONS AND PERSPECTIVES

This master thesis was carried out in partnership with RND©. The aims of the laboratory experiments were to characterize the drying kinetics of pineapple slices in a laboratory scale tunnel dryer and to develop a mathematical model of the drying kinetics. The influence of the air velocity and the slice thickness was investigated. The results have shown that a thinner thickness leads to a shorter drying time as well as a higher air velocity. At the beginning of the drying operation, it seems to vary with the moisture content and the air velocity. Actually, the internal and external heat mass transfer must be considered at the beginning of the drying operation. However, the external transfer can be neglected and the drying kinetics is mainly influenced by the internal diffusion after a certain period of time. It is also noticed that the maximum drying rate was reached after a short transitory period of 5 minutes on average.

Based on the Fick's second law of diffusion, a mathematical model could be established. The unknown parameter, the effective diffusion coefficient could be determined by the comparison between the experimental data and the mathematical model. Actually, the least square criterion was used to find the best fitting of the mathematical model with the experimental results. The effective diffusion coefficients obtained vary from $2.34\ 10^{-10}$ to $5.57\ 10^{-10}\mathrm{m}^2/\mathrm{s}$ and depend on the air velocity as well as on the slice thickness. Actually, the thinner the slice thickness is, the smaller the effective diffusion coefficient is. The observation was similar for the air velocity even if it was less significant. Although the results obtained in simulation do not show perfect agreement with the corresponding experimental data, the model can give a good estimation of the real behaviour of the drying kinetics of the pineapple slices. The deviations observed at the beginning can be due to the non inclusion of the external mass transfer in the model.

On the one hand, the supervision of the new processing centre needed to be ensured in Uganda as well as the construction of the ventilated solar tunnel dryers. In order to facilitate further construction of the ventilated solar tunnel dryers, an instruction manual was written. During the construction, some practical suggested improvements were implemented to increase the lifetime of the solar dryer. Some flowcharts were realised for the new processing centre. On the other hand, suggested advice was provided to the farmers in order to improve the drying process such as the implementation of the use of a mandolin to ensure a constant slice thickness and it leads to a homogeneous drying operation. The introduction of monthly meetings allows the farmers to share their experience. As the drying took more than one day, plastic foil was introduced on each open site of the ventilated solar dryer for the night to prevent an overly high humidity.

In Uganda, a first kind of experiments was carried out to make the comparison between the mass of the raw fresh pineapples and the mass of the dried pineapple slices. This investigation was requested by RND©. Thanks to the experiments, it can be concluded that

86 kg of fresh pineapples were requested to use the ventilated solar dryer at its maximum capability. Actually, these 86 kg of raw pineapples produces 30 kg of pineapple slices. After the drying and sorting processes, 3.9 kg of dried pineapple slices could be obtained.

Other experiments were achieved on the ventilated solar dryer implemented last year in Uganda. The aims of these experiments were to validate experimentally the three design specifications implemented in the design methodology of the ventilated solar tunnel dryer and to calculate the efficiency of the ventilated solar tunnel dryer. These design specifications ensure a uniform and efficient drying operation if they are fulfilled. The relative humidity needs to remain far below 100% during the drying operation. The results have shown that the relative humidity remained below 20% on average when the weather conditions are favourable. An analysis of the absolute humidity confirmed that the humidity remained far below the saturation of water. It was noticed that the absolute humidity of the air at the end of the heating zone was higher than the absolute humidity of the air at ambient temperature. This observation can be explained either by a local phenomenon of air recirculation due to the natural convection or by an arrangement of the probes too close to the pineapple slices during the drying. In addition, it was also suggested that the relative humidity did not reach 100% during the night which prevents the condensation of water to take place.

The second and the third design specifications are related to the temperature within the ventilated solar tunnel dryer. The temperature of the air at the end of the heating zone and the drying zone were similar to each other during the whole drying operation. These average temperatures remained below the required design temperatures of 70-75°C. This difference can be explained by the measurement period which lasted up to 6 pm whereas it was 4 pm which was considered in the design methodology but also by the difference between the data found in literature used a priori and the experimental data measured on the field. However, adequately high temperatures were reached within the dryer during a sufficiently long period of time when the weather conditions were favourable. This observation ensured good conditions to guarantee an efficient drying operation. An attempt to estimate the efficiency of the ventilated solar tunnel dryer was achieved. The efficiency is written as the ratio of the useful energy required to evaporate water and to heat up the air to the total energy captured from the sun. The average value for the calculated efficiency is 9%.

Based on the mathematical model proposed in this master thesis, the development of a new mathematical model which takes into consideration the external mass transfer can be undertaken in further researches. The model presented in this master thesis can be implemented in the design methodology in order to improve its accuracy. In addition, further experiments on different fruits can be performed within the ventilated solar tunnel dryer in Uganda. Through further partnership with RND©, some researches related to the waste treatment of pineapple peels need to be undertaken to ensure a reliable way of disposal.

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APPENDIXES

1. Detailed calculations for the resolution of the Fick's second law

In order to solve the following system and especially the Equation (3-12) needs to be solved by using the method of separation of variables.

$$\begin{cases} \tilde{C}(z = H, t > 0) = \tilde{C}(z = 0, t > 0) = 0 & \text{(3-10)} \\ \tilde{C}(0 < z < H, t = 0) = 1 & \text{(3-11)} \\ \dfrac{\partial \tilde{C}(z,t)}{\partial t} = \mathcal{D}_{eff} \dfrac{\partial^2 \tilde{C}(z,t)}{\partial z^2} & \text{(3-12)} \end{cases}$$

The method of separation of variables starts by assuming that the solution of this problem has a particular form as written in Equation (X-13).

$$\tilde{C}(z,t) = \Psi(z)\Gamma(t) \tag{X-13}$$

Introducing Equation (X-13) in Equation (3-12) and rearranging leads to Equation (X-14).

$$\frac{1}{\Psi(z)} \frac{d^2\Psi(z)}{dz^2} = \frac{1}{\mathcal{D}_{eff}\,\Gamma(t)} \frac{d\Gamma(t)}{dt} \tag{X-14}$$

The left hand side of this equation depends only on z while the right hand side depends only on t. In order to have this equality respected, both sides should be equal to the same constant written $-\omega^2$. From the original diffusion equation, an equivalent system of differential equations needs to be solved. This system includes Equations (X-15,16).

$$\begin{cases} \dfrac{1}{\mathcal{D}_{eff}\,\Gamma(t)} \dfrac{d\Gamma(t)}{dt} = -\omega^2 & \text{(X-15)} \\ \dfrac{1}{\Psi(z)} \dfrac{d^2\Psi(z)}{dz^2} = -\omega^2 & \text{(X-16)} \end{cases}$$

General solutions to these equations are obtained by direct integration. The Equations (X-17,18) are then obtained.

$$\begin{cases} \Gamma(t) = N\, e^{-(\mathcal{D}_{eff}\ \omega^2\ t)} & \text{(X-17)} \\ \Psi(z) = A' \cos(\omega\, z) + B' \sin(\omega\, z) & \text{(X-18)} \end{cases}$$

Substituting back in the Equation (X-13) and N has been combined with A' and B' to give M and N, Equation (X-13) can be written as Equation (X-19).

$$\tilde{C}(z,t) = [A\ \cos(\omega\, z) + B\ \sin(\omega\, z)]e^{-(\mathcal{D}_{eff}\ \omega^2\ t)} \tag{X-19}$$

Thanks to the boundary condition (X-10), A is necessarily equal to 0 as $\tilde{C}(z=0, t>0)=0$. Since the other boundary condition (X-10) state for $\tilde{C}(z=H, t>0)=0$, it implies $B=0$ or $\sin(\omega\, z)=0$. $B=0$ is an uninteresting trivial solution. The resolution of the second one leads to an infinite number of solutions which can be written as Equation (X-20) with n=1,2,3,...

$$\omega_n = \frac{n\,\Pi}{H} \tag{X-20}$$

Each value of ω_n yields to a different solution. Therefore, there is an infinite number of independent solutions. By using the superposition principle, it allows to write Equation (X-21) which is a linear combination of the particular solutions.

$$\tilde{C}(z,t) = \sum_{n=1}^{\infty} [B_n \sin\,(\frac{n\,\Pi}{H}\,z)] e^{-(\mathcal{D}_{eff}\,(\frac{n\,\Pi}{H})^2\,t)} \tag{X-21}$$

The value of B_n needs to satisfy the initial condition written in Equation (X-11). The Equation (X-22) needs to be solved. For t=0, the exponential factor is equal to 1.

$$\tilde{C}(z,t=0) = 1 = \sum_{n=1}^{\infty} B_n \sin\,(\frac{n\,\Pi}{H}\,z) \tag{X-22}$$

As sin(x) is a periodic function, it can be expressed in terms of sinusoidal functions by the Fourier series method. By using the orthonormality property, Equation (X-23) can be written. Detailed calculations are given below. In order to obtain the Equation (X-23), Equation (X-22-1) needs to be solved.

$$\int_0^H \sin\left(\frac{n\,\Pi}{H}\,z\right) \sin\left(\frac{n\,\Pi}{H}\,z\right) dz = \int_0^H \frac{1-\cos\,(\frac{2\,n\,\Pi}{H}\,z)}{2}\,dz \tag{X-22-1}$$

By integrating the 2 terms separately, Equation (X-22-2) and Equation (X-22-3) are obtained.

$$\int_0^H \sin\left(\frac{n\,\Pi}{H}\,z\right) \sin\left(\frac{n\,\Pi}{H}\,z\right) dz = \frac{H}{2} + \frac{H}{4\,n\,\Pi}(\sin\,(2n\Pi) - \sin(0)) \tag{X-22-2}$$

$$\int_0^H \sin\left(\frac{n\,\Pi}{H}\,z\right) \sin\left(\frac{n\,\Pi}{H}\,z\right) dz = \frac{H}{2} \tag{X-22-3}$$

From Equation (X-22-3), the Equation (X-23) can be deduced.

$$\int_0^H \sin\left(\frac{n\,\Pi}{H}\,z\right) \sin\left(\frac{m\,\Pi}{H}\,z\right) dz = \begin{cases} 0\,, m \neq n \\ \frac{H}{2}\,, m = n \end{cases} \tag{X-23}$$

By using the orthonormality principle, the particular solution for B_n can be obtained as given in Equation (X-24). Then B_n can be introduced in the general form of Equation (X-21) which is expressed in Equation (X-25) for n=1,2,3,... In order to obtain Equation (X-24), the orthonormality principle is used as follows. Considering the initial condition (X-22) and the Equation (X-23), Equation (X-23-1) and (X-23-2) can be written. As the right hand side of the equation is equal to 1, it can be inserted on one side of the Equation (X-23-1).

$$\int_0^H \sin\left(\frac{n\,\Pi}{H}\,z\right) dz = \int_0^H \sin\left(\frac{n\,\Pi}{H}\,z\right) dz \tag{X-22-1}$$

$$\int_0^H \sin\left(\frac{n\,\Pi}{H}\,z\right) dz = \int_0^H \sum_{n=1}^{\infty} B_n \sin\left(\frac{n\,\Pi}{H}\,z\right) \sin\left(\frac{n\,\Pi}{H}\,z\right) dz \tag{X-22-2}$$

Thanks to Equation (X-22-3), Equation (X-24) can be written.

$$B_n = \frac{2}{H}\int_0^H \sin\left(\frac{n\,\Pi}{H}\,z\right) dz \tag{X-24}$$

$$\tilde{C}(z,t) = \sum_{n=1}^{\infty}\left(\frac{2}{H}\int_0^H \sin\left(\frac{n\,\Pi}{H}\,z'\right) dz'\right) \sin\left(\frac{n\,\Pi}{H}\,z\right) e^{-\left(\mathcal{D}_{eff}\left(\frac{n\,\Pi}{H}\right)^2 t\right)} \tag{X-25}$$

By solving B_n and introducing the answer in Equation (X-25). Equation (X-26) is obtained. In order to obtain the Equation (X-26), B_n needs to be calculated and then introduced in Equation (X-25). Solving Equation (X-24) leads to Equation (X-24-1) which has different values according to n values. If n is even, B_n is equal to 0 while n is odd B_n is equal to $\frac{4}{n\,\Pi}$.

$$B_n = -\frac{2}{n\,\Pi}\left(-1 + (-1)^n\right) \tag{X-24-1}$$

By introducing Equation (X-24-1) in (X-25), Equation (X-25-1) is obtained.

$$\tilde{C}(z,t) = \sum_{n=1}^{\infty}\left(-\frac{2}{n\,\Pi}\left(-1 + (-1)^n\right)\right) \sin\left(\frac{n\,\Pi}{H}\,z\right) e^{-\left(\mathcal{D}_{eff}\left(\frac{n\,\Pi}{H}\right)^2 t\right)} \tag{X-25-1}$$

As only B_n and thus $\tilde{C}(z,t)$ are different from 0 if n is odd, Equation (X-25-1) can be adapted to Equation (X-26).

$$\tilde{C}(z,t) = \sum_{n=1}^{\infty}\left(\frac{4}{(2n-1)\,\Pi}\right) \sin\left(\frac{(2n-1)\,\Pi}{H}\,z\right) e^{-\left(\mathcal{D}_{eff}\left(\frac{(2n-1)\,\Pi}{H}\right)^2 t\right)} \tag{X-26}$$

Starting from Equation (X-26), the average concentration of water can be calculated as following Equation (X-26-1). Thus, Equation (X-26-2) can be obtained.

$$< \tilde{C} > (t) = \frac{1}{H} \int_0^H \tilde{C}(z,t)\ dz \tag{X-26-1}$$

$$< \tilde{C} > (t) = \frac{1}{H} \int_0^H \sum_{n=1}^{\infty} \left(\frac{4}{(2n-1)\,\Pi} \right) \sin\left(\frac{(2n-1)\,\Pi}{H}\ z \right) e^{-\left(\mathcal{D}_{eff}\ \left(\frac{(2n-1)\,\Pi}{H}\right)^2 t\right)}\ dz \tag{X-26-2}$$

By integrating this function, Equation (X-26-3) is obtained.

$$< \tilde{C} > (t) = \frac{1}{H} \sum_{n=1}^{\infty} \left(\frac{4}{(2n-1)\,\Pi} \right) e^{-\left(\mathcal{D}_{eff}\ \left(\frac{(2n-1)\,\Pi}{H}\right)^2 t\right)} \left[\frac{2H}{(2n-1)\,\Pi} \right] \tag{X-26-3}$$

Finally, Equation (3-13) can be written.

$$< \tilde{C} > (t) = \frac{8}{\Pi^2} \sum_{n=1}^{\infty} \frac{1}{(2n-1)^2}\, e^{-\left(\mathcal{D}_{eff}\ \left(\frac{(2n-1)\,\Pi}{H}\right)^2 t\right)} \tag{3-13}$$

2. Followed development to obtain the theoretical function

Based on the experimental function, it was required to find a theoretical function which was as close as possible to this experimental function. This Appendix section explains how the theoretical function was defined based on the experimental one. $M(t)$ is the mass of the pineapple slice at time t, whereas M_0 and M_d are the initial mass of pineapple slice introduced in the dryer and the final dried mass in the dryer respectively.

$$f_{exp}(t) = \frac{M(t) - M_d}{M_0 - M_d} \tag{3-14}$$

Based on Equation (3-14), the dried mass obtained in the oven after 24h (m_f) is subtracted from each term of the equation. Then, each term is divided by the volume of the pineapple slice in order to bring out the definition of the concentration of water. The volume is defined as the surface Ω multiplied by the thickness H. Thus, Equation (3-14-1) can be written.

$$f_{exp}(t) = \frac{\frac{M(t) - m_f}{\Omega H} - \frac{M_d - m_f}{\Omega H}}{\frac{M_0 - m_f}{\Omega H} - \frac{M_d - m_f}{\Omega H}} \tag{3-14-1}$$

By using the following definitions presented in Table 15, Equation (3-14-2) can be obtained.

Concentration of water (kg of water per m³ of pineapple slice)	Definition
$\boldsymbol{C_{eq}}$	$\frac{M_d - m_f}{\Omega H}$
$\boldsymbol{C_0}$	$\frac{M_0 - m_f}{\Omega H}$
$< C > (\boldsymbol{t})$	$\frac{M(t) - m_f}{\Omega H}$

Table 15: Definitions of the concentration of water

$$f_{theo}(t) = \frac{< C > (t) - C_{eq}}{C_0 - C_{eq}} \tag{3-14-1}$$

Based on the definition of $< C > (\boldsymbol{t})$**,** Equation (3-14-2) can be written.

$$f_{theo}(t) = \frac{1}{H} \int_0^H \frac{C(z,t) - C_{eq}}{C_0 - C_{eq}} dz \tag{3-14-2}$$

By using the definitions expressed in Equation (3-9) and Equation (X-26-1), the following equation (3-15) can be written.

$$f_{theo}(t) = < \tilde{C} > (t) \tag{3-15}$$

3. Graphs obtained with the software Mathematica©

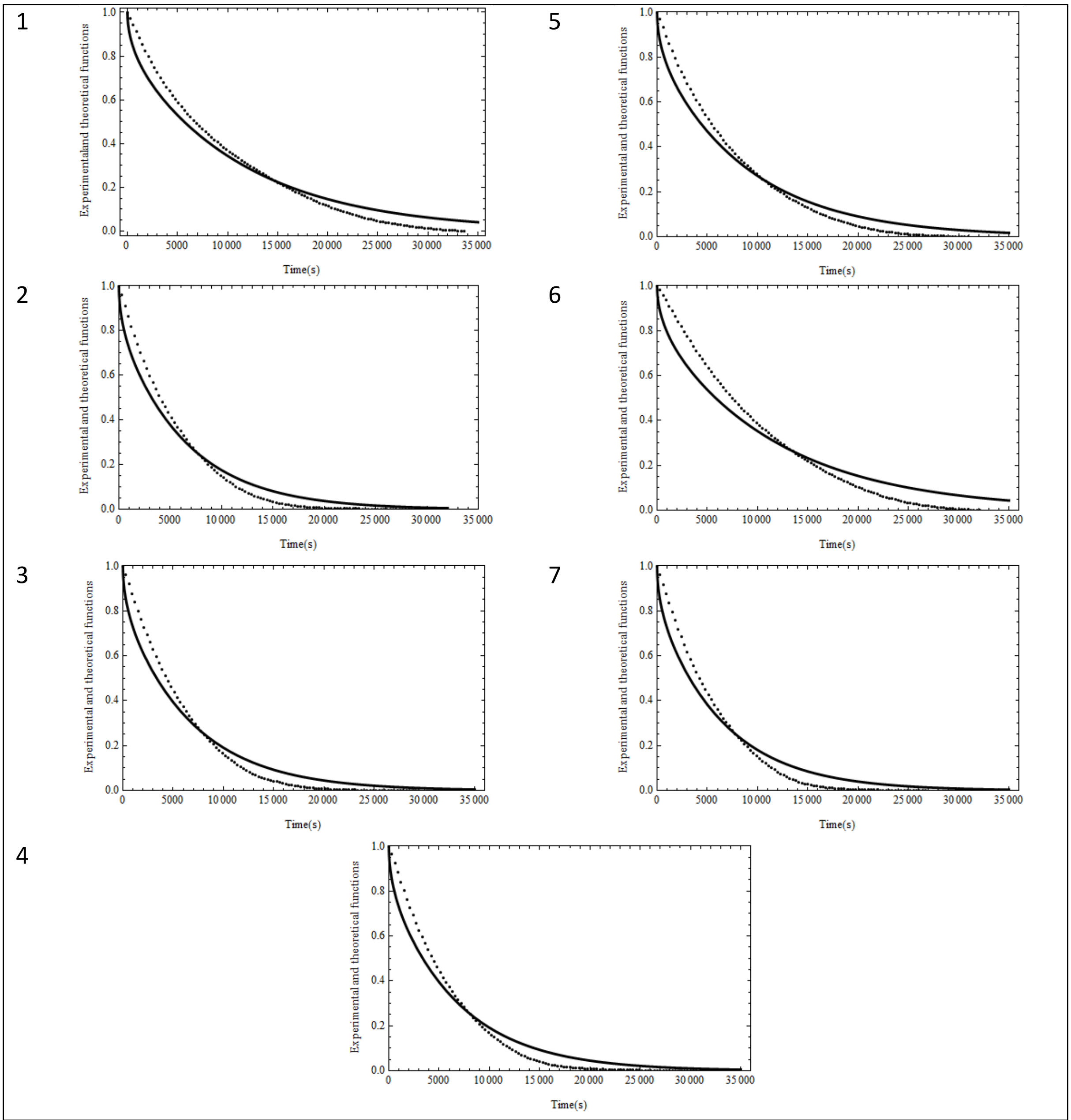

Figure 27: Graphs obtained with Mathematica©. Theoretical and experimental functions are represented.

Experiment	Conditions	$\mathcal{D}_{eff}$ (m²/s)	Least Square difference
1	65°C-18Nm³/h-8mm-SC	$5{,}560\ 10^{-10}$	0.28
2	65°C-13Nm³/h-6mm-SC	$5{,}570\ 10^{-10}$	0.23
3	65°C-13Nm³/h-4mm-SC	$2{,}343\ 10^{-10}$	0.28
4	65°C-17Nm³/h-6mm-DAM	$5{,}254\ 10^{-10}$	0.29
5	65°C-13Nm³/h-6mm-DAM	$3{,}997\ 10^{-10}$	0.26
6	65°C-8Nm³/h-6mm-DAM	$3{,}035\ 10^{-10}$	0.53
7	65°C-13Nm³/h-4mm-DAM	$2{,}433\ 10^{-10}$	0.29

Table 16: Experiment conditions, effective diffusion coefficient and least square difference calculated for each experiment

4. Instruction manual for the construction of the ventilated solar tunnel dryer

The original Instruction manual for the construction of the ventilated solar tunnel dryer was adapted to this master thesis. Actually, all the pictures are normally bigger in order to facilitate the understanding of the builder.

A. LIST OF THE REQUIRED MATERIAL AND BUDGET

Material	Quantity	Price per Unit(UGX)	Total Price (UGX)	Additional cost (UGX)	Final Cost (UGX)
Wood	30	6000	180,000	Transport: 80,000 for 100=24,000 Cuttings: 26*800=20,800	224,800
Wood preservative	≃0.5L	200,000 for 5L	20,000	/	20,000
Nails	1.5: ½ kg 2: ½ kg 3: 1 kg 4: 1 kg 5: 1 kg	6000	24,000	2000[1]	26,000
Wood for fans	1	20,000	20,000	5000	25,000
Iron sheets	6	20,000	120,000	20,000 (Try to buy for 2 dryers at once)	140,000
Papyrus	3	10,000	30,000	20,000 (Try to buy for 2 dryers at once)	50,000
Dried grass	5	4000	20,000	10,000	30,000
Black Paint	4L	40,000	40,000	2000[1]	42,000
Paraffin	1L	3000	3000	2000[1]	5000
Small nails	1	6000	6000	2000[1]	8000
Hinges	2 pairs	4000	8000	2000[1]	10,000
Small hinge	2	3000	3000	2000[1]	5000
Lock	3	3000	9000	2000[1]	11,000
Plastic foil[2]	29.25m²	1.2/m²	(35.1€) 133,801	133,801	267,602
Fans[2]	4	6.27€	(25.08€) 95,605	95,605	95,605
Mosquito net	1/3	10,000	3333	5000	8333
Mosquito net for trays[2]	7.6m²	1.25/m²	(9.5€) 36,214		36,214
Solar panel	1	150,000	150,000		
Electric wire	1m	1000	1000	2000[1]	3000
Sugar	2 or 3	200	600	2000[1]	2600
Scratch				Stiching:	
TOTAL					**1,343,973**

[1] The idea is to minimize the transport price by buying these different material stuffs together.
[2] These 3 materials are imported from Europe. This explains the expensive price for the transport.

B. PLAN OF THE CONSTRUCTION

The plan for the construction is presented in this section.

1. Construction of the Framework

2. Consolidation and Arrangement of the Framework

3. Construction and Superposition of the 4 Layers

4. Construction of the Dryer Doors and the Different Sides

5. Implementation of the Covered Surface

6. The Final Result

C. CHECKLIST

The different points expressed in this section, **need to be checked** in order to avoid heat losses during further drying operations.

- During the 3rd step, the thickness of the dried grass needs to be of 8 cm (3in) thick before stuffing it.
- The iron sheet needs to be black painted homogeneously in order to absorb more heat.
- Pieces of wood need to be placed behind the doors, inside the dryer in order to block them and to ensure a good airtight behaviour.
- There is only one side which is opened during the drying. It is the end side with the mosquito net. All the rest should be covered, closed all the time.
- On the top of each side of the framework, a small strip of Plastic foil should be installed. The small strip of plastic should be on the corner of each side to avoid all the friction between the main plastic foil and the wood. This step allows to avoid further degradation of the plastic foil which covers the whole dryer.
- Plastic foil needs to be completely tight and fit perfectly with the structure.
- There are only 2 sides with removable plastics: one on the fans side and the other on the mosquito net.

D. CONSTRUCTION OF THE FRAMEWORK

This manual is written to explain how to build the RND's Tunnel Solar Dryer. In order to build the dryer in the best way, please follow carefully these instructions. First, consider the best location to install the dryer. It should be in a sunny zone where there is a limited wind.

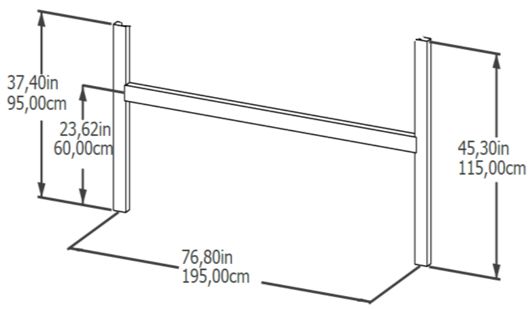

Figure 28 Ventilated solar tunnel dryer foot

First, 2 pieces of wood as shown in Figure 28are required. They are represented by feet 1 and 2 in Figure 29. Then, the foot number 3 is constructed as the feet 1,2. The only difference is that the horizontal timber at the middle height should be lower of 5 cm in order to ensure a flat surface of the bottom of the dryer as seen in Figure 30. Then, feet 4,5 are connected by allowing the horizontal piece of wood to be stuck on them. This can be achieved by doing a notch in feet 4 and 5. Then, the framework can be assembled by connecting all the pieces together as shown in Figure 31.

Once the 5 transversal sections are connected with the 4 pieces of wood (3.60m) (2 on each side). Then, 4 timbers of 3.60 m each are placed on the top of the dryer. On the top, the two sides can be linked together by inserting 5 pieces of wood. Be careful of the level of the bottom of the dryer, it should be completely flat. Put each foot on a stone as shown in Figure 30 to protect the feet from humidity of the ground. As it can be seen in Figure 30, an extra piece of wood will be needed to ensure to have a flat surface. Figure 31 shows the finished framework.

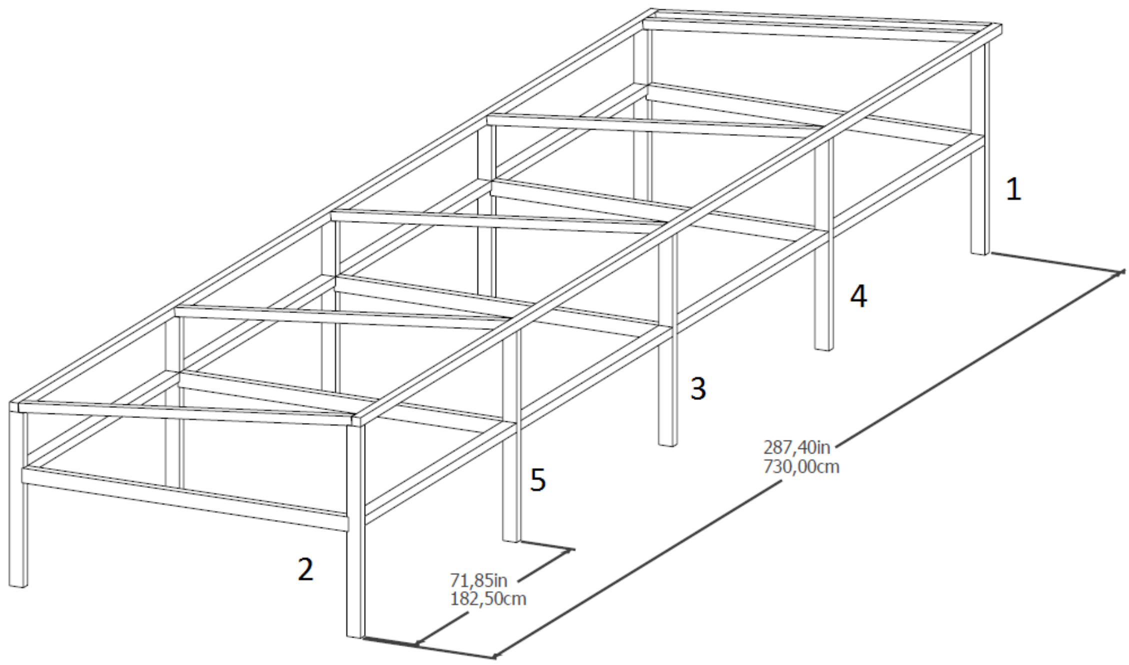

Figure 29 Ventilated solar tunnel dryer structure

Figure 30: Picture of the ventilated solar tunnel dryer structure

Figure 31: Picture of the ventilated solar tunnel dryer structure

E. CONSOLIDATION AND ARRANGEMENT OF THE FRAMEWORK

Once the basic framework is finished, each section should be consolidated with 2 squares of wood (a) and horizontally with 2 other timbers (b) in Figure 32. Squares of wood can even be added on the long side as shown in Figure 33 to sustain the long timbers inserted in step n 1.

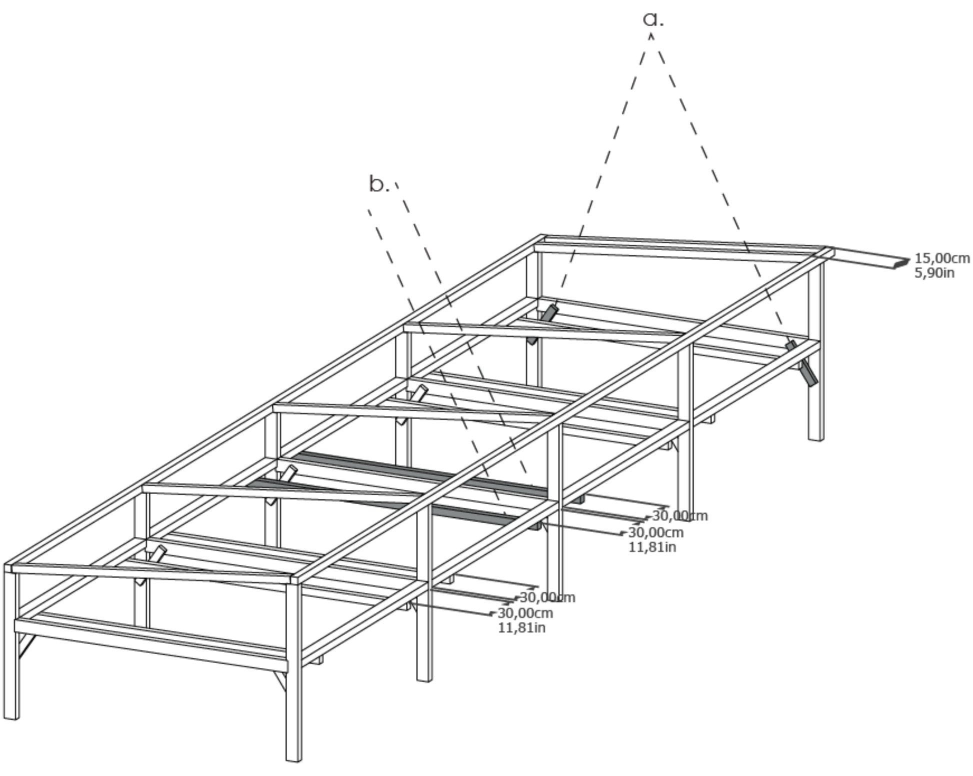

Figure 32: Solidification of the ventilated solar tunnel dryer structure

In order to avoid spoilage of the plastic foil, a piece of wood is added as shown in Figure 34 to block the trays when they will be introduced within the dryer.


Figure 33: Squares added to improve the robustness

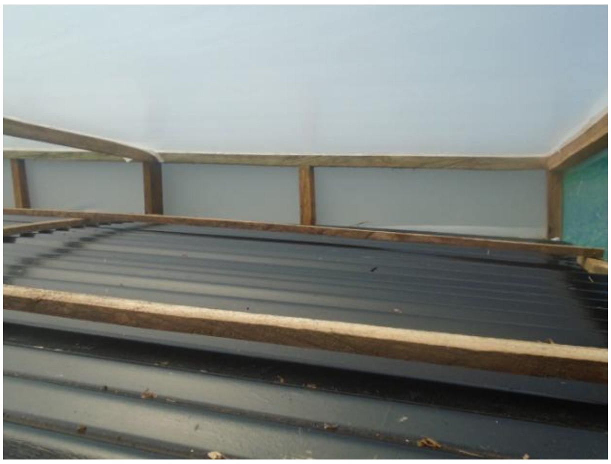
Figure 34: Piece of wood added to protect the plastic sheet when the trays are introduced

F. CONSTRUCTION AND SUPERPOSITION OF THE 4 LAYERS

4 layers need to be prepared for this step. They are placed on the top of each other. For this step, do not forget to have a flat surface in order to avoid spoilage of the materials or create disturbances within the dryer. The aim to achieve for this layer is to be an insulator in order to avoid loss of heat. For all the layers, the whole ground surface should be covered.

- The lowest layer is called “carpet” which is actually a layer of papyrus.
- Then, a layer of dried grass is placed on the top of the papyrus. The thickness of the dried grass should be **at least** equal to 8 cm (3in) before stuffing it. Do not hesitate to stuff it as much as it is possible.
- On the top, iron sheets are positioned on the whole surface. They are then black painted to ensure a good heat absorbance. They have to be homogeneously painted.
- 2 pieces of wood need to be added on the top of the iron sheets to maintain the trays. These pieces of wood need to allow as smooth as possible a good sliding of the trays when they are introduced.

All these steps are presented in Figure 35 and are placed within the dryer as shown in

Figure 36 and Figure 37.

Please, perform these steps very carefully to avoid any spoilage of the surface and thus avoiding heat loss.

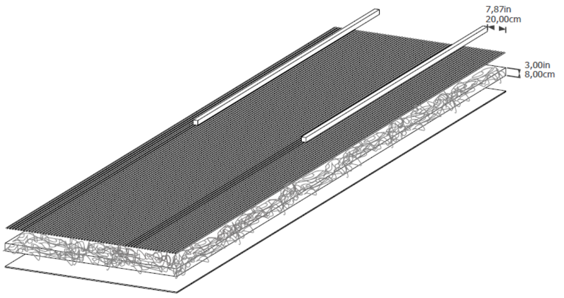

Figure 35: Layers placed on each other to form the bottom of the ventilated solar tunnel dryer. They form an insulator bottom

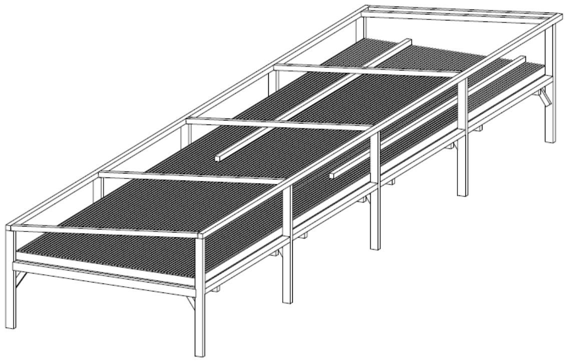

Figure 36: Insertion of the layers within ventilated solar tunnel dryer structure

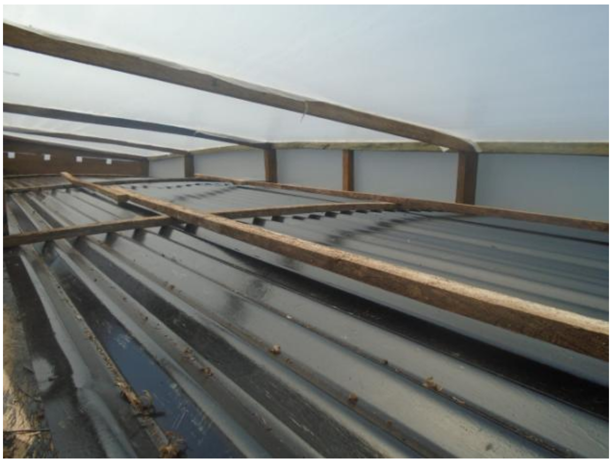

Figure 37: Inside of a ventilated solar tunnel dryer

G. CONSTRUCTION OF THE DRYER DOORS AND THE DIFFERENT SIDES

In this step, 3 different structures are added to the framework as shown in Figure 38.

- The first structure written as (a) is supposed to host the 4 fans. Each hole measures 5X5 cm (1.97 in). This piece will be inserted on one side of the dryer.
- The dryer needs 2 doors (b) in order to introduce and remove the trays from the dryer. 2 pieces of wood need to be added within the dryer behind the doors to block them and ensure the dryer to be airtight in case of wood deviation as presented in Figure 39. The doors must have locks to close them.
- A small door (c) is inserted close to the fans as presented in Figure 38. It ensures to reach them easily. This door requires also a lock to be closed.

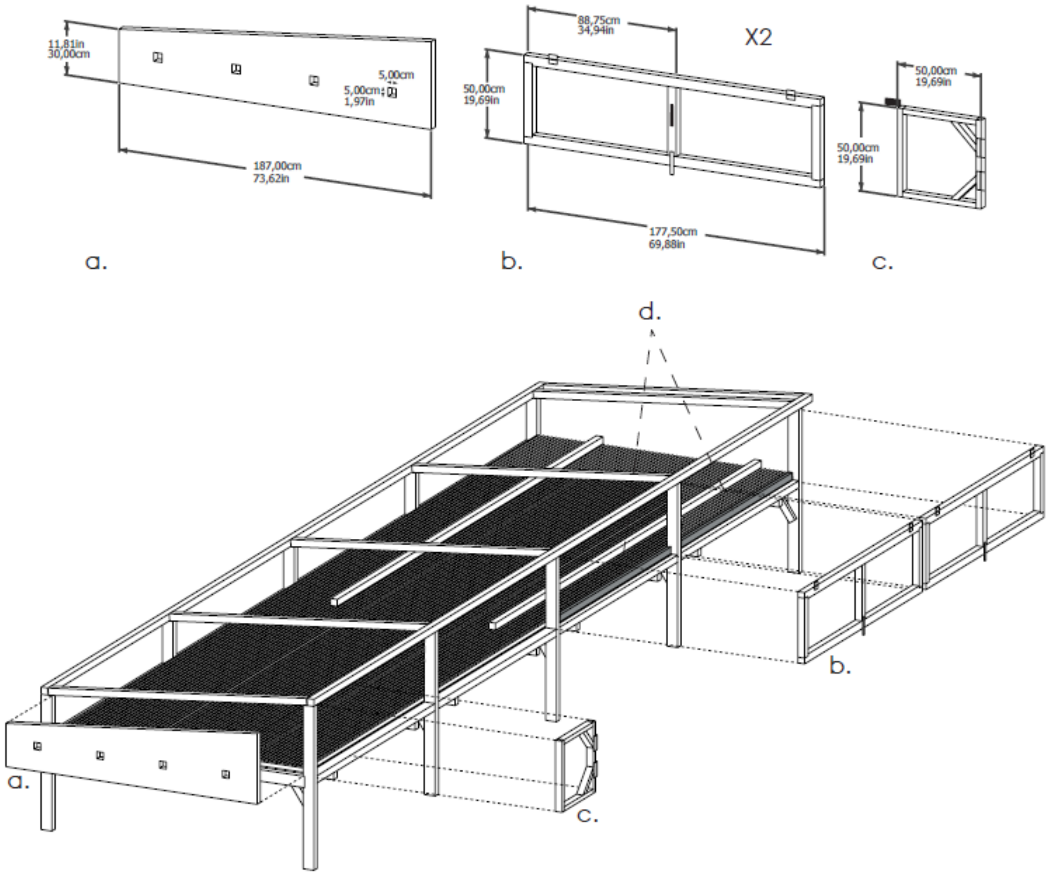

Figure 38: Doors insertion on the ventilated solar tunnel dryer

Figure 39: Piece of wood to ensure an airthightness

H. IMPLEMENTATION OF THE COVER SURFACE

The fans are inserted in the foreseen holes (a). They should be inserted such that the airflow is coming from outside to enter in the dryer. Leave the wires of the fans outside to connect them easily to a solar panel or any electricity source.

Then, the mosquito net is fixed on the opposite side of the dryer (b).

Small strips of plastic are placed on the corner of each side of the dryer's top to avoid spoilage of the plastic foil.

After, the plastic foil is arranged on the whole dryer (c) and it is fixed on the entire dryer, except on the 2 extremities. On the small sides, the plastic must be removable on (a) to access easily the fans and allow the air to enter. On (d) side as well, it allows this extremity to be open during the drying and be closed during the night.

All these steps must be perfectly followed to fit completely the structure in order to avoid heat loss. All these steps are shown in Figure 40.

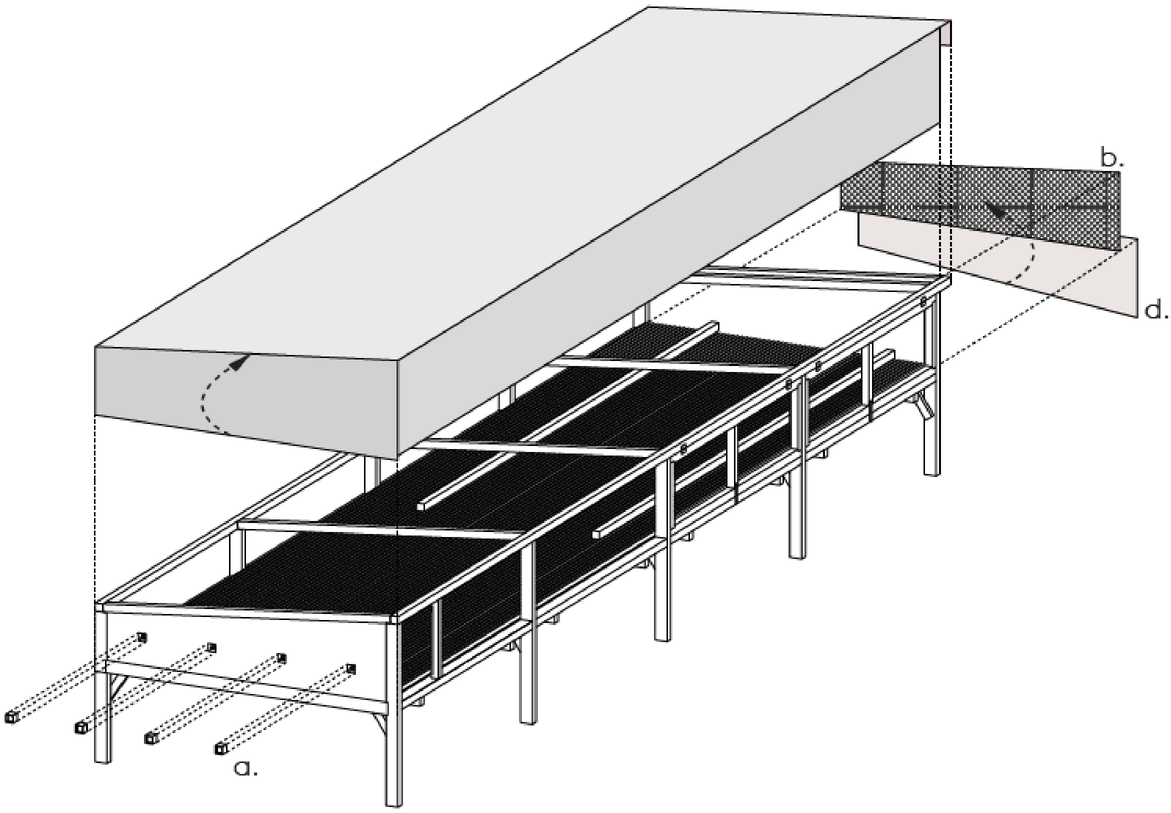

Figure 40: Anti-UV plastic sheet to cover the ventilated solar tunnel dryer

I. THE FINAL RESULT

In order to use the dryer, you should have made 4 trays to support the fresh fruits.

Please respect their dimensions. They are wood-framed and mosquito net is tight inside the frame. The final result is presented in Figure 41 and Figure 42.

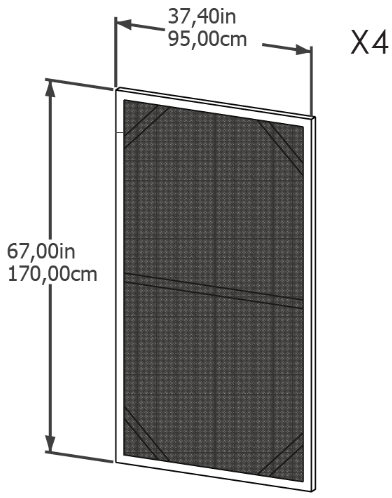

Figure 41: Tray structure

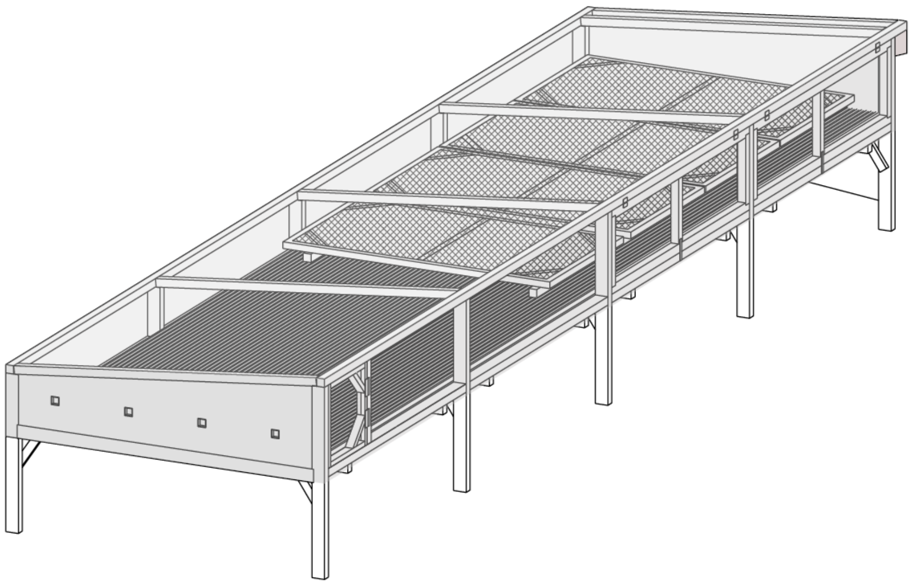

Figure 42: Final scheme of the ventilated solar tunnel dryer

This dryer was sized for pineapples drying. However, an adaptation to other fruits such as mangoes, papayas, jackfruits,... is still possible by adapting the drying and the heat zone dimensions.

5. Small scale solar tunnel dryer technology factsheet

Overview	
Name of the technology	Solar tunnel dryers for small scale farmers' communities constructed with a majority of material found on site (except anti-UV plastic foil, mosquito net and fans)
Global description	This solar dryer is suitable for fruits drying. The dryer is a wood-framed box covered by an anti-UV plastic foil. Two parts are defined within the dryer: the heating zone and the drying zone. The length of each zone can be adapted regarding the fruits to dry. The construction of the dryer requires a carpenter. However, it can be used by illiterate users. The drying time for pineapple slices is about 2 days of sunshine. Every 2 days, 30kg of fresh pineapple slices can be introduced within the dryer and will lead to obtain around 5 kg of dried pineapples.
History of the dryer	In the framework of a partnership between the TIPs department of the Université libre de Bruxelles and The NGO Refugee Next Door (RND©) which is active in Uganda. RND© is interested by promoting the fair trade of dried pineapples in Uganda. First, the design methodology to size the solar dryer was established by Pauline Talbot in the framework of her PhD (2015). Second, the first solar tunnel dryer was constructed by Mathilde Lhote in Uganda during her master thesis (2015).
Context	During the peak harvest season, the supply of fresh fruits exceeds considerably the demand on the local and regional market. As Uganda is a landlocked country with a lack of transport infrastructure, the fruit drying is a solution to reduce the waste during the harvest season and provide added value products to the farmers. In this way, RND© has a direct impact on local farmers by provide them reliable source of incomes and RND© try to lead them to be financially independent. RND©'s goal is to alleviate poverty through socio-economic and education projects.
Typical users	The solar drying process can be handled by anyone even if a training session could be required in order to use the dryer in an optimal way. This solar dryer has been implemented in Uganda and it works perfectly. It can be used by illiterate people or people who attended school.
Technological aspects	
Complete description of the dryer	The tunnel solar dryer is composed of 2 zones: the heating and dry zones. They are connected in series. The air is entering by one side of the dryer where the fans are implemented. The fans can be supplied by a photovoltaic panel. The airflow is heating up from the entrance of the heating zone towards the dry zone. This increase in temperature is possible thanks to solar radiations and the greenhouse effect which is present within the dryer. The bottom of the dryer is constructed of a layer of papyrus, superimposed by a layer of dried grass and finally a black painted iron sheet used as a heat absorber. The two first layers ensure the bottom of the dryer to be insulating. The fresh products are laid on trays in the dry zone whereas the heating zone is product-free. The drying zone is designed to support 4 trays of 7.5kg of fresh pineapple slices each (30kg in total). The products undergo both direct solar flux energy and indirect energy from the hot airflow. The released water vapour is carried away by the forced airflow. The exit side is

	completely covered by a mosquito net while the entire top is recovered with an anti UV transparent plastic foil. It is important to ensure an airtight structured to prevent flags and insects to enter the dryer and reducing the heat losses. After 2 days of sunshine on average, around 5 kg of dried pineapples are obtained.
Description of the drying process	First, the raw pineapples are washed. Then, they are peeled and cut in slices. After, the heart of the pineapples is removed. Once the slices of pineapple are ready, they are laid on the trays which are introduced within the dryer. As soon as the pineapple slices are dried enough, they are removed from the dryer. The dried pineapple slices are sorted and packed in a plastic bag. They are stored in a dry and dark place.
Production cycle	30kg of fresh pineapple/ dryer. It takes 2 days of sunshine to dry all the pineapples Around 5 kg of dried pineapples is obtained after these 2 days.
Work load – required preparation time	For one dryer, around 45 pineapples need to be processed. The best way to organise the work is to allocate a specific task to everyone. One person is peeling; the other one is cutting the slices, and so on... The assembly-line method. The time is hardly measureable as the farmers use to operate multiple dryers. A work is required to process the raw pineapples. At the end of the day, it is required to check the state of pineapple slices. If they are ready, they need to be removed, sorted and packed.
Operation time within a year	The solar dryer can be used as soon as the weather is sunny and it depends also on the fruits harvest. For the pineapples in Uganda, It operates especially during January, February, March, July, August and September. It corresponds to the harvest of pineapples.
Expected lifetime of the technology	The solar dryer requires maintenance as it is constructed mainly in wood. The average lifetime of a dryer is between 3 to 5 years depending on the performed maintenance work.
Time to build a solar dryer	A carpenter takes 5 to 6 days when he constructs it by himself. If an assistant is hired, the construction time is around 3 to 4 days.
Possible issue for replication	To have the anti-UV plastic foil, mosquito net and the fans as well as the photo voltaic panel. The anti-UV plastic foil is required to avoid fast spoilage.
Economic aspects	
Investment price	A dryer costs 1,483,973 UGX (±393€).
Estimated quantities	Around 86kg of fresh pineapple is necessary to obtain 30 kg of fresh pineapple slices. On average, 5.1kg of dried pineapple slices are obtained. After sorting, 76% of the dried pineapple is kept which is equal to 3.9 kg.
Production cost	A major advantage of this solar dryer is that it does not require any energy supply. The only energy supply is the solar energy. The estimated efficiency of the dryer is equal to 9%.

Environmental aspects	
water	Water is only required to maintain the cleanliness of the dryer. The dryer has no environmental impact. The trays need to be washed after every use and the inside of the dryer needs to be washed between each operation while the outside should be washed every 2 or 3 days.
Social aspects	
Employment	For one dryer, one person can handle it. However, as soon as there are more than one dryer, it is better to allocate a specific task to every person. One person for peeling, one person for cutting the slices, one or 2 people to remove the heart and one person to lay the pineapple slices on the tray. 4 or 5 people are needed when there are more than one dryer.
Gender	The work can be handled by women. This work allows the empowerment of the woman within the household. It can be handled by old men as well.
Land ownership	The ground surface of the dryer is 7.30m x 1.95 m = 14.235 m^2.
Useful contact information	
Name of contact people	Benoit Haut (bhaut@ulb.ac.be) Mathilde Lhote (mathilde.lhote@ulb.ac.be) François- Xavier Willaert (fxwillaert@gmail.com) Alexandre Donner (aldonner@ulb.ac.be)
Key words	Solar tunnel drying, Fruit drying, Uganda, pineapple, post harvest waste reduction

The structure of this technology factsheet was based on the structure applied by Quentin Jonckheere [64].

6. Example of flowchart created for the new processing centre

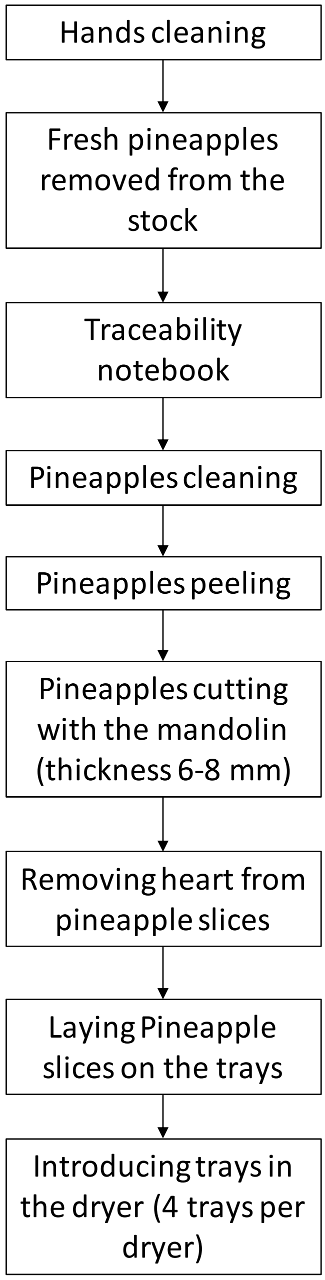

Figure 43: Example of a flowchart written to explain the pineapple drying process to future workers in the new processing centre

7. Relative humidity and temperature measured on site

The Table 17, Table 18 and Table 19 present the measurements performed on site regarding the relative humidity, temperature, time of drying and global solar radiation.

	Test 1	Test 2	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9
Date	11/02	21/02	01/03	03/03	11/03	15/03	18/03	23/03
T_{amb} ($\pm$ 1°C)	33	28	33	27	34	35	30	31
HR_{amb} ($\pm$ 3%)	32	68	42	74	44	34		55
$T_{air,heat}$ ($\pm$ 1°C)	57	43	65	42	60	66	68	53
$HR_{air,heat}$ ($\pm$ 3%)			9				8	
$T_{air,dry}$ ($\pm$ 1°C)	50	39		44	69	71	64	55
$HR_{air,dry}$ ($\pm$ 3%)	15	43		27	10,4	7	14	25
Starting time(h)	10,54	10,17	9,00	9,00	9,00	9,50	11,42	9,67
End time (h)	18	17	18,00	18	18	18	18	18
F_s ($\pm$ 0.5 W/m²)	722	349	604	365	740	832	648	568

Table 17: Temperature, relative humidity, starting time, end time and global solar radiation were measured for the day 1 of each experiment. The measurements correspond to the average value over the day of drying

	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9
Date	12/02	22/02	29/02	02/03	04/03	12/03	16/03	19/03	24/03
T_{amb} ($\pm$ 1°C)	28	32	31	33	32	32	34	31	33
HR_{amb} ($\pm$ 3%)	65	55	52	44	53	56	47		50
$T_{air,heat}$ ($\pm$ 1°C)	43	55	62	67	59	64	69	63	56
$HR_{air,heat}$ ($\pm$ 3%)			14	12				16	
$T_{air,dry}$ ($\pm$ 1°C)	36	58			66		72	60	63
$HR_{air,dry}$ ($\pm$ 3%)	45	15			15		10	21	13
Starting time(h)	9	9	9	8,5	8	8	9	8	9
End time (h)	18	18	18	18	18	18	14,3333	18	17
F_s ($\pm$ 0.5 W/m²)	432	607	805	642	628,5	790	914	603	579

Table 18: Temperature, relative humidity, starting time, end time and global solar radiation were measured for the day 2 of each experiment. The measurements correspond to the average value over the day of drying

	Test 1	Test 2	Test 9
Date	13/02	23/02	25/03
T_{amb} ($\pm$ 1°C)	34	33	32
HR_{amb} ($\pm$ 3%)	42	56	54
$T_{air,heat}$ ($\pm$ 1°C)	67	64	60
$HR_{air,heat}$ ($\pm$ 3%)			
$T_{air,dry}$ ($\pm$ 1°C)	51	61	66
$HR_{air,dry}$ ($\pm$ 3%)	18	16	10
Starting time(h)	9	9	9
End time (h)	18	14,3333	13,6667
F_s ($\pm$ 0.5 W/m²)	697	779	726

Table 19: Temperature, relative humidity, starting time, end time and global solar radiation were measured for the day 3 of each experiment. The measurements correspond to the average value over the day of drying

8. Tables related to the calculation of the efficiency of the solar tunnel dryer

	test1			test 2			test 5	
	day 1	day 2	day3	day 1	day 2	day3	day 1	day 2
$m_{water,evap}$(g)	16282	5761,32	2022,25	5341,25	10125,8	1597,6	7508	6404,85
$m_{water,evap}$ (kg)	16.28	5.76	2.02	5.34	10.13	1.60	7.51	6.40
$T_{air,heat}$ (°C)	57	43	67	43	55	64	42	59
$T_{air,dry}$ (°C)	50	36	51	39	58	61	44	66
T average (heat& dry) (°C)	53	40	59	41	57	63	43	63
T_{amb} (°C)	33	28	34	28	32	33	27	32
T_{dp} (°C)	14	21	19	22	22	23	22	21
F_s (W/m²)	722	432	697	349	607	779	365	629
t_d (h)	7.5	9.0	9.0	6.8	9.0	5.3	9.0	10.0
t_d (min)	448	540	540	410	540	320	540	600
t_d (s)	26856	32400	32400	24600	32400	19200	32400	36000
ε_{sky}	0.83	0.84	0.84	0.84	0.85	0.85	0.85	0.84
T_{sky} (K)	288.8	288.8	293.4	289.4	293.4	295.3	288.7	293.0
$F_{IR,atm}$ (W/m²)	401	387	415	388	409	416	384	408

Table 20: Useful information regarding the calculations of the efficiency of the solar tunnel dryer for experiments 1, 2 and 5

	test 6	test 7		test 9		
	day 1	day 1	day 2	day 1	day 2	day3
$m_{water,evap}$(g)	13353	14539	1565	12460	6495,614	592
$m_{water,evap}$ (kg)	13.35	14.54	1.57	12.46	6.50	0.59
$T_{air,heat}$ (°C)	60	66	69	53	56	60
$T_{air,dry}$ (°C)	69	71	72	55	63	66
T average (heat& dry) (°C)	65	69	71	54	60	63
T_{dp} (°C)	20	17	21	21	21	22
T_{amb} (°C)	34	35	34	31	33	32
F_s (W/m²)	740	832	914	568	579	726
t_d (h)	9.0	8.5	5.3	8.3	8.0	4.7
t_d (min)	540	510	320	500	480	280
t_d (s)	32400	30600	19200	30000	28800	16800
ε_{sky}	0.84	0.83	0.84	0.84	0.84	0.84
T_{sky} (K)	294	292.6	294.8	291.8	293.9	293.2
$F_{IR,atm}$ (W/m²)	416	416	418	402	413	409

Table 21: Useful information regarding the calculation of the efficiency of the solar tunnel dryer for experiments 6, 7 and 9

	Test 1			Test 2			Test 5		Test 6	Test 7		Test 9			
	Day 1	Day 2	Day 3	Day 1	Day 2	Day 3	Day 1	Day 2	Day 1	Day 1	Day 2	Day 1	Day 2	Day 3	**Average**
E_u (MJ)	50.2	20.7	19.3	19.7	46.1	17.9	32.2	47.3	61.3	63.3	22.9	48.3	38.1	16.4	**36.0**
E_{solar} (MJ)	400.4	352.6	456.8	239.8	443.9	293.6	322.1	502.7	505.6	513.0	348.5	390.5	383.7	243.7	**385.5**
η_{std} (%)	13	6	4	8	10	6	10	9	12	12	7	12	10	7	**9**

Table 22: Overall efficiency of the solar tunnel dryer calculated for the experiments performed in Uganda