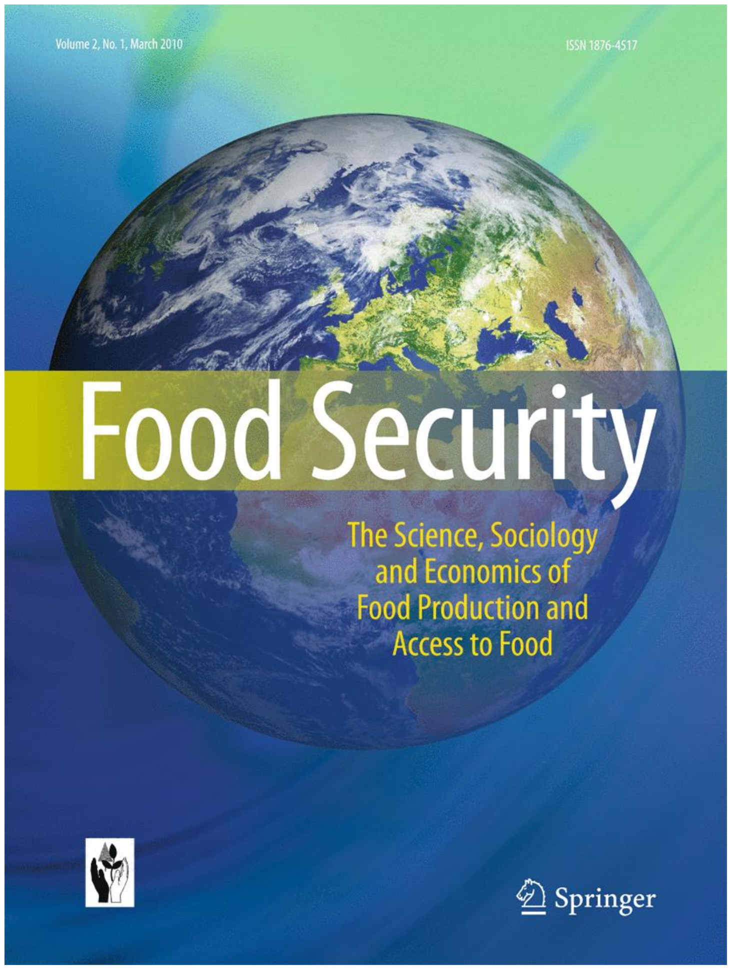
ISSN 1876-4517, Volume 2, Number 1



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Food Sec. (2010) 2:71–80
DOI 10.1007/s12571-009-0049-4

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ORIGINAL PAPER

Implementation of a rational drying process for fish conservation

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Received: 29 September 2009 / Accepted: 18 December 2009 / Published online: 27 January 2010
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Abstract Fishing is a traditional activity that is widespread in West Africa. One of the greatest problems for fishermen and a cause of lack of food accessibility is the difficulty in conserving fish. Drying is a widely used technique in sub-Saharan Africa for preservation of fish. However, drying is a complex process, making the construction and calibration of efficient drying devices challenging. This paper presents the construction and calibration of five mobile fish dryers in Mali and, for one of them, development of a method for its use. The performances achieved far exceeded those of traditional solar dryers as drying was faster and the fish were not contaminated by being exposed to flies. Furthermore, construction and user manuals were written for the local fishermen which were well understood as the fishermen were able to disassemble and reassemble the dryers when they were required to be moved.

Keywords Food conservation · Food self-sufficiency · Solar drying · West Africa

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Introduction

In sub-Saharan Africa, 32% of the population regularly experiences chronic malnutrition (FAO 2006), and in Mali, the figure is 28%. Most African countries are not self-sufficient in food and are dependent on imports to ensure the food security of their people. Taking into account recent price spikes of foodstuffs on the world market, this situation is becoming intolerable for an increasingly large proportion of the world's population. According to the Food and Agriculture Organization of the United Nations (FAO) and Organisation for Economic Co-operation and Development (OECD), various factors will keep prices "at higher average levels than in the past" (FAO & OECD 2008).

Fishing is a traditional activity which is widespread in Mali. In 2005, the national production of fish was estimated to be 92,798 tons, and the value generated was estimated to be 90,000 million FCFA (= ~ US$ 200 million), representing around 4.2% of the gross domestic product (FAO 2007). Eighty percent of the production is concentrated in the Niger Inland Delta (FAO 2007). The Mopti area, situated in the centre of the Niger Inland Delta, is one of the biggest fishing areas, with an annual production estimated by the PCDA[1] of between 37,000 and 66,000 tons.

One of the greatest problems for fishermen and a cause of lack of food accessibility is the difficulty of conserving fish. Until recently, because of the lack of ice accessibility, around 75% (reaching 80–90% in the Niger Inland Delta) of the fish were transformed through smoking, searing (the fish is placed between two layers of straw which are lit) or drying before being commercialised (FAO 2007). This is now changing because of the increased marketing of fresh

[1] Programme Compétitivité Diversification Agricoles (Mali)—Agricultural Competitively and Diversification Program (Mali).

fish, which is more lucrative. However, marketing of fresh fish requires access to ice which is not available everywhere in the Niger Inland Delta. Therefore, in this area many fishermen still need to preserve fish by means other than refrigeration: 53% are smoked, 32% seared and 14% dried (van der Pol and Boomsma 2007). With a tonnage estimated between 10,000 and 20,000 and prices around 2,000–4,000 FCFA/kg, the value of the transformed fish in the Niger Inland Delta is estimated to be between 20,000 and 40,000 millions FCFA per year (van der Pol and Boomsma 2007). Around 100,000–200,000 persons are involved in the fish preservation chain, most of them being among the poorest and living far from main roads, where access to ice is difficult (van der Pol and Boomsma 2007).

Food preservation methods such as canning, practised in more economically developed countries, are inappropriate for sub-Saharan Africa as they generally require high energy consumption and advanced technology. Drying is widely used in Africa because the temperature to which food has to be raised is quite low. Mostly the sun is used as a heat source. Further advantages of drying, besides longer shelf life, include reduction in weight of the food, facilitating its transport and storage, maintenance of its nutritive properties and added value to some products. Dried fish may be preserved from 3 to 6 months depending on the storage conditions (FAO 2007).

Traditional drying in Africa is typically performed by direct exposure to the sun. The food is spread on the soil surface, which is usually covered with straw in order to protect the fish from contamination. Unfortunately, this method often causes degradation of the product. In particular, when drying or selling fish in the open air, insecticide must be applied to prevent eggs being laid by flies or other insects, which every year cause a number of poisonings (van der Pol and Boomsma 2007). Because of this, consumers prefer to buy fresh fish, and the transformed fish market is only partially developed.

Preservation by smoking has the drawback of needing large amounts of wood and raises the issue of deforestation. It is becoming more difficult to find smoking wood and the quality of the product is reduced when other combustible materials such as straw or dung are used (van der Pol and Boomsma 2007).

Modern drying techniques are more efficient and more hygienic but are also more complex. Therefore, most equipment is still developed empirically, and this can lead to various problems for large-scale units such as the amount of energy used and the quality of the product (Mujumdar 2007). Yet, modern drying units, based on a rational design, have recently been developed in West Africa for other food products such as fruits and vegetables (Nonclercq et al. 2009), showing the feasibility of upgrading traditional drying methods.

CORDAID (The Hague), IER,[2] ASM,[3] APH[4] in Bandiagara, AFAR[5] in Mopti, and KIT[6] in Amsterdam have pooled their strengths in the IER-Trans Mopti program, which aims to enhance and widen food transformation and conservation techniques, to professionalise those working in the industry, particularly women, and to promote innovation and access to markets.

In 2006, a modern fish drying technique was tested on a fixed dryer (Innotech 2009) and in January 2007, during an evaluation with CORDAID partners, it was concluded that the product obtained from it was of high quality. Furthermore, tests on the product conducted by the Food and Consumer Product Safety Authority of Holland were positive and the product could be preserved without the use of insecticide (van der Pol and Boomsma 2007).

After seeing the good results of the CORDAID project in the transformed fish field, fish traders were positive regarding the possibility of enhancing the transformed fish market (van der Pol and Boomsma 2007). In December 2007 it was decided to focus on fish transformation, and to include the creation of a value-added chain for fish drying, by improving the drying process. A pilot study, in collaboration with ULB[7] and AFAR, was initiated with the aim of improving local traditional methods for drying fish, using mobile dryers rather than direct exposure to the sun. Mobile fish dryers were chosen because they are best suited to the nomadic way of life of many fishermen. Moreover, as the drying units use solar power, there is no environmental cost as there would be for the use of pesticides or of wood to generate heat.

First indicators on the financial benefits of the dryer are promising. Owing to the better quality of the product it commands an estimated 10% premium which translates to an extra 100,000 FCFA income per annum. This can be used to defray the capital and maintenance expenses of the dryers.

This paper presents part of the work achieved on this pilot project, consisting of the installation of five mobile dryers in Youwarou (a fishing town situated in the Mopti area), the development of an efficient method for their use, comparison of the results with traditional drying techniques, and testing the ease of use and comprehension of the user and construction manuals, written for the local fishermen. This trial in a single village is the first step of a

[2] Institut d'Economie Rural—Institute of Rural Economy. It was represented by its CCRA (Centre Régional de Recherche Agricole—Regional Centre of Agricultural Research) in Mopti.
[3] Action Sociale Mopti—Mopti Social Action.
[4] Actions Promotion Humaine—Human Promotion Actions.
[5] Action de Formation et d'Autopromotion Rurale—Action of Rural Formation and Self-Promotion.
[6] Koninklijk Instituut voor de Tropen—Royal Tropical Institute.
[7] Université Libre de Bruxelles—Free University of Brussels

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larger project. In the second step, to be taken in 2 years time, IER-Trans Mopti plans to extend the project by building a large number of dryers for the whole country. Here the production of user-friendly manuals will be crucial.

The aim was to dry the maximum amount of fish in the minimum time, assuming 10 h sunshine per day, while maintaining the optimal organoleptic quality of the dried fish. Quality was determined by direct sensory evaluation by consumers and their acceptance of the product, which was usually reduced to a maximum of 30% of its original weight. A temperature of 60°C inside the dryer was chosen as this corresponds to the optimum trade-off between minimising microbial growth and minimising deterioration (tanning as well as taste and smell alterations occur at temperatures above 65°C; Lantry and O'Gorman 2007). Because the method was designed for dryers that already existed, the parameters relevant to the dryers were fixed.

Materials and methods

The mobile dryers were all constructed in Youwarou, but at different sites, according to a design developed in 2006 by KIT and a Dutch tent building firm (Birdland) on the basis of the Hohenheim solar tunnel dryer (Innotech 2009).

Fig. 1 A typical mobile dryer (**a**) Schematic representation (**b**) Photograph of a practical realisation

Figure 1a presents a schematic view of a typical mobile dryer, while Fig. 1b shows a practical example. The dryer has a tunnel form, composed of a black plastic tarpaulin on the ground and a transparent plastic sheet for the roof. Fish are placed between the two on a net that is suspended above the plastic tarpaulin on the ground. An air blower, powered by photo-voltaic cells, is positioned at one end of the tunnel and a mosquito net at the other. The dryer is divided into seven sections, the first two of which are empty and serve as pre-heaters for the inlet air and the other five contain fish.

The operation of the dryer is characterized by three parameters: v, the velocity of the air delivered by the ventilator, t_s, the drying time (the time of the operation), and M_f, the mass of fish placed in the dryer. The last approximates to 50 kg for most fish, being the maximum amount that can be placed in the dryer without their touching each other.

For commercial reasons, the final quality of the dried fish is mainly evaluated on organoleptic considerations. However, it is assumed that the fish will be well dried if:

- the temperature at the end of the heating zone is close to 60°C,
- a mass reduction of 70% is obtained at the end of the operation,
- the temperature at the end of the drying zone is not >75°C (to avoid the fish being cooked),
- the relative humidity of the air at the end of the drying zone is not greater than 25% (to avoid a significant heterogeneity of the humidity in the dryer and therefore a significant heterogeneity of the drying rate, that would lead to a product of uneven quality).

It can be shown (see Appendix) that if v=0.3 m/s, t_s=6 h and 15 min and M_f=50 kg a good quality product is achieved, providing that the average solar flux is about 700 W/m^2 and the ambient temperature outside the dryer about 40°C. The solar flux and the atmospheric temperature may, of course, vary during the year, but for typical conditions in Mali, their influence on the selection of operating conditions leading to good quality drying is limited. Such variation is corrected by regulating the airflow manually and placing screens on the solar panels, according to the temperatures measured at the end of the heating zone. Furthermore, natural regulation occurs because high intensity sunlight causes both a higher airflow (because the solar panels collect more power) and a higher temperature in the dryer, with the higher airflow tending to compensate for the higher temperature.

However, it is well known that drying kinetics are often not limited by the rate at which energy is brought to the product that has to be dried but rather by the kinetics of water removal (liquid or vapour) and by its movement (diffusion and/or convection). The global rate of water evaporation in the dryer can be two or even three times less than the one predicted by Eq. 19 (see Appendix). This is especially true for large fish, from which it is more difficult to extract water. Therefore, the theoretical operating conditions should be set for small fish but the drying time for larger fish should be determined by experimentation.

A construction and a user manual were designed for the local fishermen. As the vast majority of Bozos fishermen are illiterate the manuals consist of very simple, schematic explanations. The construction manual, which is mainly intended for members of Malian non-governmental organisations (NGOs), is based upon a series of steps on how to build the solar dryers, including general recommendations. The user manual consists of a large schematic drawing, explaining every phase of the drying process, allowing fishermen the opportunity of understanding the whole process. For example, it shows which parameters should be recorded, when the temperature should be measured and when the fish should be weighed.

A comparison was made with a hangar fish dryer (Fig. 2), which is a modern version of traditional drying on straw laid on the ground. The fish are laid on wood boards attached to upright wooden struts and the whole structure is covered by a mosquito net. The drying conditions are, therefore, the same as the ambient atmospheric ones.

The experiments were performed on the available dryers with fresh fish provided directly by the fishermen. For experiments lasting more than 1 day, air was not blown during the night as the blowers are solar powered. Temperature was recorded during all of the experiments at the end of the second segment, corresponding to the end of the pre-heating section. All of the tests began at 9 AM.

Fig. 2 Example of a conventional hangar-type dryer

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Results

Five identical mobile dryers were installed successfully and used to dry different quantities of three different species of fish (Table 1) Temperatures in the dryer during these six experiments varied considerably, generally peaking at 4–6 h and again at 28–30 h (Fig. 3).

As all experiments began at 9 AM, these correspond to the middle of the day and early afternoon. At these times, the inlet air is at its maximum temperature and the pre-heating zone presents the largest heat transfer. The figure also shows that the maximum temperature never exceeded 65°C, demonstrating good temperature control.

Detailed analysis of the drying is not possible based on the available data. Indeed, multiple factors changed from one experiment to another, making interpretation quite complex. For instance, the relatively low temperature achieved in Experiments 1 and 3 were due to particularly bad weather conditions. However, trends can be detected. Comparison between Experiments 1 and 2, based on Table 1 and Fig. 3, shows that higher temperatures, such as those achieved in Experiment 2, tend to reduce drying time considerably. Besides, the drying time needed for small fish (*Mormyrus rhume*) was close to the theoretical drying time identified in the Appendix (except for Experiment 1 due to the bad weather). As predicted in the previous section, the drying time was longer for medium sized fish (*Tilapia niloticus*), and even longer for large fish (*Hydrocion porskali*).

In these experiments, the fixed limit to ensure product quality was reached. However, the quality of the product is still satisfactory. This illustrates the fact that a potentially too restrictive limit was chosen in the approach presented in the appendix to evaluate the optimal drying conditions. The variability of the final mass loss illustrates the difficulty of deciding the time at which drying should be halted. Indeed, if kept in the dryer, the fish would lose still more water. The chosen objective of 70% mass loss should not be considered as a strict criterion; rather, the main objective is that the fish should be acceptable to the consumer. This can only be judged by eye.

Data obtained for experiments 4 to 6 (Table 1) are remarkably similar, demonstrating the robustness of the process. However, even with the variable ambient conditions none of the drying times required to reduce the water content of the fish to an acceptable level exceeded 20 h and this was achieved without degrading the product. This result compares favourably with the traditional hangar drying technique which required at least 30 h for 15 kg of *Hydrocion porskali* fish to reach the desired 70% mass loss. Moreover, there was no spoilage of the fish as they were not exposed directly to the sun.

The manuals produced for the construction and operation of the dryers were well understood and, indeed, several fishermen, who had to move their campsite in order to follow the river, took the dryer with them and were able to re-build it without any help. They also monitored the drying process as they were taught by a supervisor. The supervisor, who was in charge of evaluating the use of the dryers, reported that all fishermen involved with the project were delighted with the dryers and their ability to assemble and operate them.

Discussion

In this paper, the construction and use of five mobile dryers for fish conservation has been presented. The dryers developed an internal temperature of about 60°C and allowed the drying of 50 kg of fish in around 1 day with 70% weight reduction. They were installed in Youwarou, Mali, where their performances far exceeded that of traditional solar dryers. Construction and user manuals were written for the local fishermen which were well understood and used.

Hygiene problems raised with traditional fish dryers were overcome in two ways. First, dust, sand fly and insects no longer contaminated the fish as they were not exposed to open air, thus obviating the need for the use of insecticides. Second, the products retained all their nutritive properties because they were not directly exposed to the sun and were dried at controlled temperatures lower than that of the damage threshold. As a result, it is hoped that customers will perceive fish dried in this way are better than those dried by traditional methods and will be willing to pay a higher price for them.

Owing to the simplicity of construction and usage of the units, they are robust and durable. Moreover, they are easy to repair and to dismantle at the end of their life span with a

Table 1 Drying times required for different species and corresponding amounts of fish

Experiment	Species of fish	Initial mass (kg)	Mass loss (%)	Total drying time (h)	Maximal temperature reached (°C)
1	*Mormyrus rhume*	29	59.31	20	57.2
2		47	70.21	8	64.0
3	*Tilapia niloticus*	33	72.12	12	41.0
4	*Hydrocion porskali*	56	69.64	17	60.0
5		55	73.64	16	61.0
6		40	62.5	16	57.7

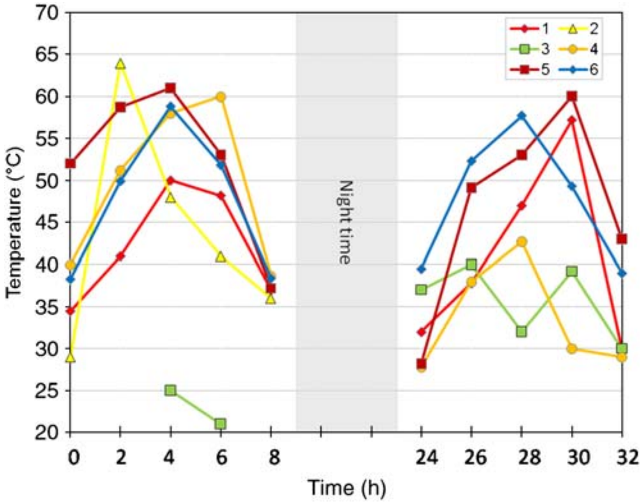

Fig. 3 Temperatures recorded in the dryer for six experiments

view to recycling the components. Finally, the project was implemented entirely in collaboration with various local stakeholders, so as to encourage its sustainability.

The prototype could be improved mainly in two ways. First, the current solar panels, used to empower the fan, are too powerful and therefore smaller ones could be used instead, which would allow cost reduction and easier maintenance. Second, temperature regulation, in order to keep it at about 60°C in the dryer, is currently performed manually, which is time consuming and results in additional costs. A regulation module is currently being constructed in order to allow the maintenance of a temperature of about 60°C in the dryer without human intervention.

The work presented in this paper is a pilot project on a relatively small scale that has been realised in the framework of the IER-Trans Mopti program. It is hoped that it will be adopted by other districts in Mali and even other countries of West Africa to the advantage of those for whom fish are the basis of their livelihoods.

Acknowledgments The authors acknowledge financial support from CORDAID (Netherlands), the Commission Universitaire pour le Développement (CUD, Belgium) and the Applied Science Faculty of the Université Libre de Bruxelles. The authors acknowledge the assistance and contribution of Abdoulaye Timbely (AFAR vice president) and Mamadou Samake (AFAR).

Conflict of interest The authors declare that they have no conflict of interest.

Appendix

Notations

$c_{p,a}$	heat capacity of air (at 60°C, $c_{p,a}$ is approximately equal to 1,000 J/kg/K)
D_h	hydraulic diameter of the dryer (m)
e	thickness of the plastic (10^{-3} m)
F_s	solar flux (W/m^2)
g	acceleration of gravity (m/s^2)
Gr	Grasshof number (-)
h	height of the dryer, see Fig. 1a (0.43 m)
h_n	heat transfer coefficient between the covering plastic and the ambient air (W/m^2/K)
$h_f(v)$	heat transfer coefficient between the air in the dryer and the covering plastic, as a function of the air velocity in the dryer (W/m^2/K)
l	width of the dryer, see Fig. 1a (1.25 m)
L_c	see Fig. 1a (m)
L_k	massic latent heat of water vaporization (at 60°C, L_k is approximately equal to 2,250 kJ/kg)
L_m	molar latent heat of water vaporization (at 60°C, L_m is approximately equal to 40,500 J/mol.)
M_f	initial mass of fish in the dryer (kg)
MM_a	molar mass of air (29 10^{-3} kg/mol.)
MM_w	molar mass of water (18 10^{-3} kg/mol.)
Nu_f	Nusselt number for forced convection (-)
Nu_n	Nusselt number for natural convection (-)
p_{atm}	atmospheric pressure (101,325 kg/m/s^2)
$p_{sat}(T)$	saturation pressure of water at temperature T (kg/m/s^2)
p_0	saturation pressure of water at temperature T_0 (12,349 kg/m/s^2)
Pr	Prandtl number (-)
R_g	perfect gas constant (8.314 J/mol./K)
R_w	global rate of water evaporation in the dryer (kg of water/s)
Re	Reynolds number (-)
t_s	drying time (s)
T_0	reference temperature (50°C)
T_{atm}	atmospheric temperature (K)
$T_s(z)$	temperature of the air at position z in the dryer (K)
$T_{p,i}(z)$	temperature of the inner side of the covering plastic, at position z in the dryer (K)
$T_{p,e}(z)$	temperature of the outer side of the covering plastic, at position z in the dryer (K)
U(v)	global heat transfer coefficient between the air in the dryer and the atmosphere, as a function of the air velocity in the dryer (W/m^2/K)
v	velocity of the air in the dryer (m/s)
x	length of the dryer, see Fig. 1a (10.5 m)
x_c	length of the heating zone in the dryer, see Fig. 1a (3 m)
x_d	length of the drying zone in the dryer, see Fig. 1a (7.5 m)
Y(z)	humidity of the air at position z in the dryer (kg of water / kg of dried air)
Y_0	humidity of the ambient air (kg of water / kg of dried air)

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$Y_{sat}(T)$ saturation humidity of air at temperature T (kg of water / kg of dried air)

z position in the dryer. $z=0$ at the entrance in the dryer. $z=x$ at the outlet of the dryer (m)

Greek letters

β air dilation coefficient (1/K)

ε_a emissivity of air (0.9)

ε_p emissivity of plastic (0.9)

λ_a thermal conductivity of air (at 60°C, λ_a is approximately equal to 2.8 10^{-2} W/m/K)

λ_p thermal conductivity of plastic (0.17 W/m/K)

μ_a dynamic viscosity of the air (at 60°C, μ_a is approximately equal to 2 10^{-5} kg/m/s)

ρ_a volumetric mass of air (kg/m^3)

σ Stefan-Boltzmann constant (5.67 10^{-8} W/m^2/K^4)

Ω area of the triangular section of the dryer perpendicular to the air flow (m^2)

Assumptions

- The air is considered as a perfect gas.
- As the amount of water in the air in a well operated dryer remains limited (see below), it is assumed that the flow rate of air throughout the dryer is conserved and can be considered as being the flow rate of dried air.
- In the calculations below, the physico-chemical properties of air (ρ_a, $c_{p,a}$, λ_a, β, μ_a) are always evaluated at 60°C.

Preliminary calculations

The following relations can be written:

$$\Omega = \frac{hl}{2} \tag{1}$$

$$D_h = \frac{4\frac{lh}{2}}{2L_c + l} \tag{2}$$

L_c can be approximated as follows:

$$L_c = \sqrt{\frac{l^2}{4} + h^2} \tag{3}$$

Therefore, Ω=0.25 m^2, L_c=0.76 m, D_h=0.39 m.

As the air is considered as a perfect gas:

$$\rho_a = \frac{p_{atm}\mathrm{MM}_a}{R_g T} \tag{4}$$

$$\beta = \frac{1}{T} \tag{5}$$

Therefore, at T=60°C, ρ_a=1.1 kg/m^3 and β=3.0 10^{-3} 1/K.

U(v) can be expressed as follows:

$$\frac{1}{U(v)} = \frac{1}{h_f(v)} + \frac{e}{\lambda_p} + \frac{1}{h_n} \tag{6}$$

It can be easily demonstrated that:

$$T_{p,e}(z) = T(z) - \left(\frac{1}{h_f(v)} + \frac{e}{\lambda_p}\right)U(v)(T(z) - T_{atm}) \tag{7}$$

Three dimensionless numbers are classically used to compute $h_f(v)$:

$$\mathrm{Nu}_f = \frac{h_f(v)D_h}{\lambda_a} \tag{8}$$

$$\mathrm{Re} = \frac{v D_h \rho_a}{\mu_a} \tag{9}$$

$$\mathrm{Pr} = \frac{c_{p,a}\mu_a}{\lambda_a} \tag{10}$$

If $10.10^3<\mathrm{Re}<120.10^3$ and $0.7<\mathrm{Pr}<120$ (it can be checked, *a posteriori*, that this condition is fulfilled for the dryer):

$$\mathrm{Nu}_f = 0.023\,\mathrm{Re}^{0.8}\mathrm{Pr}^{0.3} \tag{11}$$

Therefore, at T=60°C, $h_f(v)=4.2\ v^{0.8}$ W/K/m^2.

Three dimensionless numbers are classically used to compute h_n:

$$\mathrm{Nu}_n = \frac{h_n L_c}{\lambda_a} \tag{12}$$

$$\mathrm{Gr} = \frac{\rho_a^2 \beta g \Delta T L_c^3}{\mu_a^2} \tag{13}$$

$$\mathrm{Pr} = \frac{c_{p,a}\mu_a}{\lambda_a} \tag{14}$$

where ΔT is the temperature difference causing the natural convection (assumed here to be approximately equal to 20°C).

If $8\ 10^6<\mathrm{Gr\ Pr}<10^{11}$ (it can be checked that this condition is fulfilled for the dryer):

$$\mathrm{Nu}_f = 0.15\,(\mathrm{Re}\,Gr)^{0.33} \tag{15}$$

Therefore, at T=60°C, h_n=4.2 W/K/m^2.

The saturation pressure at a temperature T is evaluated using Clapeyron's law:

$$p_{sat}(T) = p_0 \exp\left(-\frac{L_m}{R_g}\left(\frac{1}{T} - \frac{1}{T_0}\right)\right) \tag{16}$$

It can be easily shown that:

$$Y_{sat}(T) = \frac{\frac{p_{sat}(T)}{p_{atm}} \frac{MM_w}{MM_a}}{1 - \frac{p_{sat}(T)}{p_{atm}} \frac{MM_w}{MM_a}} \tag{17}$$

Methodology

The operation of the dryer is characterized by three parameters: v, the velocity of the air delivered by the ventilator (that can be adjusted), t_s, the drying time (the time of the operation), and M_f, the mass of fish placed in the dryer. M_f approximates to 50 kg for most fish and corresponds to the maximum number of fish that can be placed in the dryer without touching each other.

It is assumed that a good drying of the fish is achieved if:

- the temperature at the end of the heating zone is close to 60°C,
- a mass reduction of 70% is obtained at the end of the operation,
- the temperature at the end of the drying zone is not higher than 75°C (to avoid the fish being cooked),
- the relative humidity of the air at the end of the drying zone is not greater than 25% (to avoid a significant heterogeneity of the humidity in the dryer and therefore a significant heterogeneity of the drying rate, that would lead to a product of uneven quality).

An energy balance on a slice [z, z+Δz] of the heating zone in the dryer yields the following equation:

$$\rho_a c_{p,a} v \Omega \frac{dT}{dz} = lF_s + l\varepsilon_a \sigma T_{atm}^4 - 2L_c U(v)[T(z) - T_{atm}] - 2L_c \sigma \left[T_{p,e}(z)\right]^4 \tag{18}$$

This equation can be numerically solved with Mathematica® for any value of v, if T_{atm} and F_s are given. In Fig. 4, $T_s(z)$ is presented for different values of v, with F_s=700 W/m^2 and T_{atm}=40°C.

It can be observed in Fig. 4 that, for F_s=700 W/m^2 and T_{atm}=40°C, a temperature of 60°C is achieved at the end of the heating zone if v=0.3 m/s.

If the drying kinetic is limited by the rate at which energy is brought to the fish, the energy consumed by the evaporation process is exactly equal to the radiative energy flux (solar + atmospheric) caught by the dryer minus the energy lost by the dryer (by radiation and heat conduction/convection). Therefore, the temperature in the drying zone is homogeneous (and written T_s) and the global rate of water evaporation in the dryer, R_w, can be calculated solving the following equation:

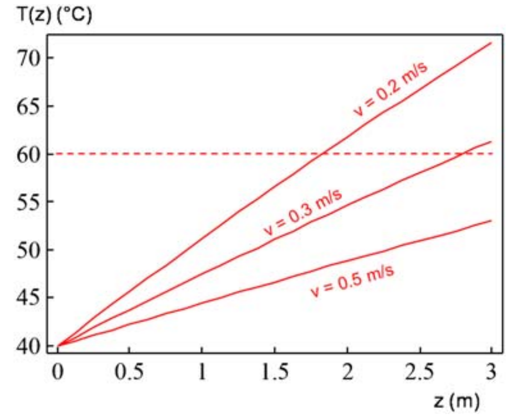

Fig. 4 Temperature of the air at position z in the heating zone of the dryer for different air velocities

$$x_d l F_s + x_d l \varepsilon_a \sigma T_{atm}^4 = 2L_c x_d U(v)[T_s - T_{atm}] + 2L_c x_d \sigma \left[T_s - \left(\frac{1}{h_f(v)} + \frac{e}{\lambda_p}\right) U(v)(T_s - T_{atm})\right]^4 + R_w L_k \tag{19}$$

If F_s=700 W/m^2, T_{atm}=40°C and v=0.3 m/s, R_w=1.9 g/s is calculated. Hence, if 50 kg of fish are placed initially in the dryer, the time needed to obtain a mass reduction of 70% is approximately 6 h and 15 min.

A mass balance on the vapour in the air in the dryer may be written as follows:

$$\rho_a v \Omega Y_0 + R_w = \rho_a v \Omega Y(x) \tag{20}$$

If F_s=700 W/m^2, T_{atm}=40°C and v=0.3 m/s, Y(x)=37 g of water per kg of air is calculated. Hence, the relative humidity of the air at the end of the drying zone is equal to 23% (T_s=61°C was used).

Therefore, if the drying kinetic is limited by the rate at which energy is brought to the fish, v=0.3 m/s, t_s=6 h and 15 min and M_f=50 kg are operating conditions that will lead to a drying of good quality, if F_s=700 W/m^2 and T_{atm}=40°C.

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