Impact of alternating drying-air flow direction on the drying kinetics of agricultural products

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Abstract: - An investigation of the rectification of non-uniformity in moisture content of dried products, arising during the drying process of agricultural products in mechanical tunnel drying facilities, by adopting the method of the airflow direction inversion is presented. The experimental task was carried out in a tunnel dryer, of 2-ton fresh tomatoes capacity. The drying conditions applied were those already used in laboratory tests with results considered as satisfying the quality criteria. This work is an attempt to analyze and determine qualitatively the validity of the concept by reporting results from the initial testing campaign during the commissioning period of the facility. The drying data have been approximated using the Page thin-layer drying equation and the results are also reported and discussed. A comparison of the drying time required to obtain uniform moisture content on the entire batches investigated, has been carried out and it was estimated that fuel savings of more than 30% could be achieved when the alternating flow direction drying process was performed.

Key words: Tunnel dryers, tomato drying, thin-layer drying, Page equation, drying curve.

1. Introduction

Drying agricultural products mechanically by means of heated air is an important and commonly employed method, offering physico-chemical stabilization by taking away part of the moisture content. If compared to the traditional open-air sun drying, presents great scientific and economic interest in being capable of achieving a considerable improvement in food quality and minimization in the wasted and spoiled dried products (Sokhansanj & Jayas, 1987)[7].

Figs, grapes, tomatoes and other fruits and vegetables are dried in tunnel dehydrators, placed on trays of different shapes stacked in mobile trolley facilities, improving in that way the flexibility and the ease of movement inside and outside the dryer. Cruess and Christie first introduced this technology, as reported by Adams & Thompson (1985), and this was then widely used from many other engineers and scientists for the drying of agricultural products (Bertin et al., 1986 and Vagenas et al., 1991). [1] [2] [8]

Drying time and product quality are recognized to be controlled by several factors such as air conditions (temperature and humidity), pretreatment of the fruit and air speed over the fruit. The lack of uniformity in the air flow conditions along the tunnel length or the frontal area has been identified as a crucial factor, causing variable moisture content among the fruits at the end of drying and affecting the product quality (Karathanos & Belessiotis, 1997). Many times the operators of the dryers regularly observe large variations in fruit moisture content even within individual trays. In the effort to ensure that the wettest fruit has reached adequate moisture content, many of the remaining fruits are overdried. In some cases, quantities of wet fruit are collected and redried for several hours using the same or other dedicated dryers. In other cases, the wet fruits from these tasks are even sun dried losing that way all the advantages of the mechanical drying. It is evident therefore that the lack of air uniformity constitutes a major problem for the drying industry. [3]

Although airflow uniformity is not dealt with explicitly as a design consideration, quite a few tunnels have turning vanes or air baffles at different location within the drying chamber, improving thus the uniformity of dried product moisture content (Adams & Thompson, 1985). The non-uniformity or even the inadequacy of the airflow inside the mechanical dryer, combined with lack of information on the suitable drying conditions for a particular product, leads to results that rarely coincide with those expected. In order to investigate the effects of the non-uniform distribution of air inside the dryer several studies has been carried out. Several investigators, (Kiranoudis et al., 1999 and Mathioulakis et al., 1998), have attempted to predict the air flow pattern inside the dryer, with the aim of suggesting methods and techniques for improvement of the aerodynamic performance of the dryer. [1] [4] [5]

In order to deal with the problem of lack of air uniformity inside the dryer, which is predominant along the flow direction, the concept of periodically inverting the airflow direction inside the drying chamber has been investigated. The inversion of the airflow direction was accomplished following a pre-programmed schedule by means of louvered dampers, properly placed inside the air ducts.

The validity of the concept and the efficiency of design have been tested by carrying out several drying tasks during the commissioning of the facility using fresh tomatoes. The tests were performed both with air flowing in the same direction during the entire task, as well as with a periodically inverted flow direction. The drying tasks were carried out under real conditions and in straight collaboration with the producers, in order to establish a realistic approach to the given problem, showing the potentialities offered by this method.

The drying kinetics of the investigated configurations was determined and then approximated using the Page model equation (Page, 1949). The drying constants thus evaluated were compared between them. [6]

2. Dryer description

A tunnel dryer of the tray type having a 2-tonnes fresh product capacity, has been installed in a rural area of central Greece, taking advantage of the availability of different agricultural products throughout the year and the drying experience of the local personnel.

The drying facility consisted of the drying chamber and the heating - ventilation unit. The drying chamber was divided into compartments having the appropriate dimensions to receive entire tray stacks. The air was drawn into the drying chamber by means of diffusing plenums equipped with perforated metal sheets in order to ensure a good uniformity of the airflow over the cross-sectional area of the drying chamber.

The air distribution and heating system consisted of the fans, the combustion chamber, the air distribution ducts, a heat recovery unit and a system of louvered dampers. Two centrifugal fans controlled by means of frequency inverters have been used to induce the circulation and recycling of the air into the drying chamber. Part of the heated air was recirculated, replenished in a certain proportion with fresh one. The fresh air was pre-heated by recovering part of the thermal load of the exhaust air using a plate heat exchanger unit. An LPG fired burner regulated for maximum combustion, was used for the heating of the drying air.

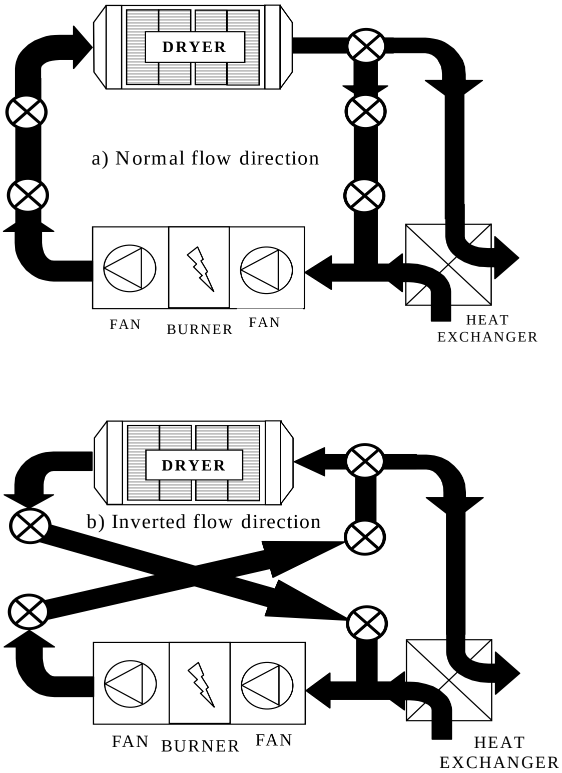

Fig 1: Diagram of the dryer and the different configurations of the airflow circulation

The air duct system circuit was equipped with a system of five properly positioned louvered dampers activated by means of on/off servomotors in order to guide the hot drying air towards the desired section of the drying chamber. In the schematic diagram reported in Fig. 1 the two different configurations a) and b) of the airflow direction, achieved by means of the air dampers as well as the positioning of the air heating and distribution system of the dryer, are clearly illustrated.

The control system consisted of the main controller board including the processing unit and the necessary software. The processor has been programmed in the C language and a user-friendly environment was developed. The controller acts directly on the servomotors of the direction dampers, as well as on the burner activation relay in order to establish the user designated conditions. Besides that, the controller has the capability of storing all the data from measurements, as well as the airflow-direction conditions. The drying conditions (temperature, velocity and direction of drying air) were thus easily controlled during the drying period and the drying data continuously recorded on a portable computer. The data from all sensors were transferred and elaborated by the process unit commanding the different systems of the dryer.

The drying chamber was equipped with all necessary sensors in order to control the drying process and airflow direction, as well as the monitoring of the drying parameters. Two air temperature sensors of the Pt100 type were placed in the middle of the inlet and outlet sections of the drying chamber. A combined temperature and humidity sensor of the OMEGA HX94C type was placed in the middle of the roof of the drying chamber, providing important indications about the drying air conditions inside the chamber. The velocity of drying air was measured by means of an ALNOR AVT55 sensor placed in the middle position of the right-hand section of the drying chamber and the value was adjusted either manually or automatically by acting directly to the frequency inverters of the fan motors. The weight loss of selected trays inside the dryer was monitored during the drying using a portable balance of 20 kg capacity and a minimum division of 20 g.

3. Materials and methods

Several drying tasks have been carried out using basically tomatoes having 95 % w.b. of initial moisture content. The target moisture for the dried tomatoes was of 10% w.b. The fresh product was cut in two halves and then placed on wooden trays used for this application. The drying conditions applied for all tasks specified an air temperature of 65^{o}C and an air velocity of 1.5 m/s. In all tasks the air temperature achieved in the drying chamber was 65 ± 4^{o}C and the air velocity was 1.4 m/s. The drying conditions had already been used in previous laboratory tests for the same product and the results obtained were considered as satisfying the quality criteria. In order to have a comparison of the investigated concept in the first task, the drying air flow direction was taken from the right-hand side to the left. Only after gaining enough experience with controlling the dryer at those conditions, drying tasks with the direction of the airflow periodically reversed have been tried out. The best drying scenario was that of repeated cycles of right-hand side airflow for 2 hours followed successively by 4 hours of left-hand side airflow.

The estimation of the performance of the dryer took place by monitoring the weight loss of three different trays during the entire drying task and the drying curves were obtained. The monitoring of the operation was always done on site. The trays selected for monitoring were those placed in the centerline of the drying chamber one from the right-hand side stack, one from the left-hand side and one from the middle stack. The moisture content and the water activity of the fresh product as well as of the dried one were measured by collecting representative samples from different parts of the drying chamber.

4. Results and discussion

Comparison of the drying kinetics by running the dryer according to the two following drying scenarios has been made:

a. Keeping the airflow constantly flowing from the right-hand side of the dryer during the whole drying task.

b. Alternating periods of 2 hours interval, in which the airflow enters from the right-hand side of the dryer, followed by a 4-hour interval in which the airflow enters from the left-hand side of the dryer. The alternating periods have been continued until the end of the drying task.

In both of them, fresh tomatoes, of the variety used for industrial purposes were cut in two equal pieces, placed in the trays keeping the concave part down. In both cases these were dried for about 23 h until a moisture content of about around 15% w.b. was obtained. The comparison has been made by monitoring the weight loss of the three trays and the results are depicted in the drying curves. The drying curves of all tasks conducted, are being reported below in Figs. 2 and 4, where the moisture ratio MR (defined as the ratio of the moisture at time t to the initial moisture content) and the drying rate (expressed in gr of water per second) were plotted versus time.

After an examination of the drying curves reported a short period, which practically coincides with the heating up period is revealed.

During this period the drying rate reaches a maximum value, followed then by a period into which the product dries following a falling drying rate. The constant drying rate period, which is typical in the case of fruits and vegetables, is either very small or does not exist at all. The initial value of drying rate for the stack near the inlet is almost twice the value of the opposite side stacks. This fact may be attributed to the predominant direct effect of air temperature on the drying rate, as clearly shown in the figures, which becomes less important after approximately 10~15 h. After this period of time, the effect of temperature becomes less important and the drying rate is more or less uniform in all three monitored stacks.

4.1 Drying with air flowing from one direction only

The first task was that described in **a.** whereby the airflow direction was kept constant during the entire drying period, flowing from the right-hand side of the dryer to the left.

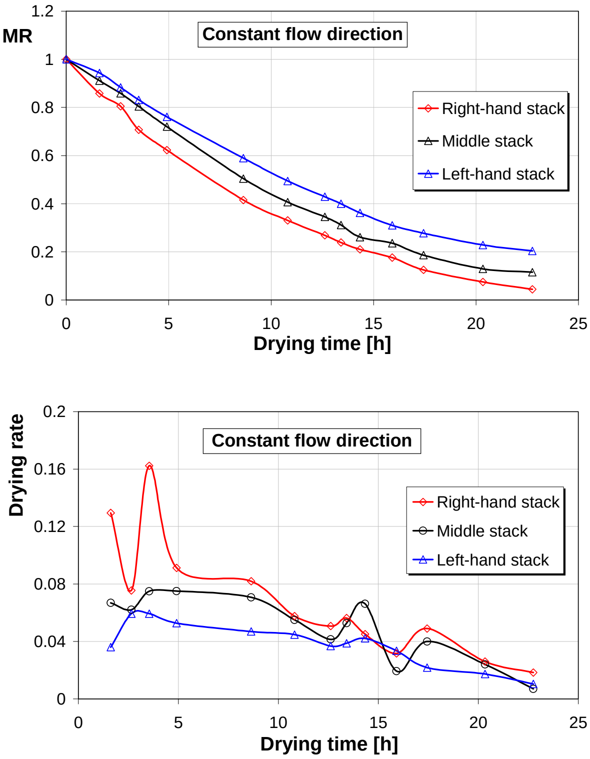

Fig 2: Drying curves for tomato drying, keeping the drying air direction constant.

In the results, shown in Fig. 2, the differences in moisture content of the three trays at the end of drying can be clearly seen. The tray close to the air inlet (right-hand side) presents a higher drying rate and low moisture content (*MR*~0.05), reached at the end of drying. On the other hand, the tray placed at the opposite part (left-hand side) presents a higher moisture content (*MR*~0.20), at the end of the drying and the tray from the middle part of the dryer an intermediate value of moisture content (*MR*~0.12).

It has to be concluded therefore that the part of batch placed on the right-hand side was subjected to overdrying. This is a common phenomenon in the practice of industrial dryers, constituting one of their main problems. The non-uniformity in final moisture content causes major problems in drying product quality and sometimes additional drying tasks are indispensable in order to compensate, giving rise to additional energy costs and time spent.

In Fig.3 an extrapolation of the drying time in order to obtain a moisture ratio of *MR*=0.1 for the “wet” stack, has been performed. It can be seen that an additional drying period of at least 8~10 h is required in order to obtain accepted value of moisture. In the meantime, the “dry” stack will have been overdried, unless it is removed from the dryer, causing penalties in time, personnel and perhaps quality degradation.

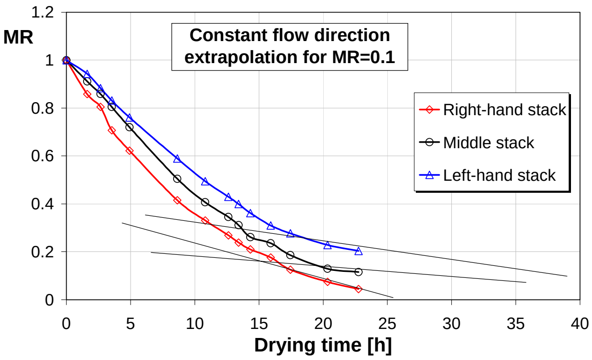

Fig 3: Drying curves for tomato drying keeping the drying air direction constant.

The additional drying time required and the resulting fuel consumption has naturally a considerable impact on the drying cost and the product quality. The above mentioned problem has been removed by following the method used in the next drying scenario.

4.2 Drying with alternating airflow direction

The second task reported is that in which the airflow direction was periodically inverted according to the fixed scenario **b.** described above. According to this scenario, periods of a 2-hour interval, in which the airflow enters from the right-hand side of the dryer, followed by a 4-hour interval in which the airflow enters from the left-hand side of the dryer were applied.

The alternating periods have been continued until the end of the drying task. In the results reported in Fig. 4, no differences in moisture content of all three monitored trays at the end of the drying can be observed. In order to ensure that the wettest product has reached an adequate moisture content, a value of *MR*~0.12, at the end of drying, for all three monitored trays has been pursued. This value of moisture content is widely acceptable for a good quality product.

As clearly shown, initially, when the drying air is flowing for 2 hours from the right-hand side of the dryer, the tray close to the air inlet exhibits the highest drying rate, as expected. The tray placed on the opposite part of the dryer presents the lowest value of drying rate and the one taken from the middle part gives an intermediate value.

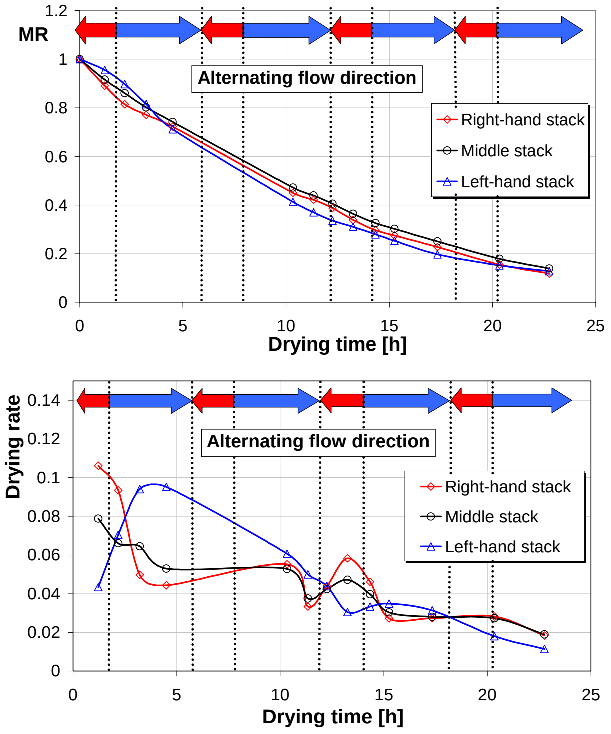

Fig 4: Drying curves for tomato drying with the airflow direction periodically inverted

This situation was promptly reversed when the drying air direction was switched, as can be clearly shown. In the subsequent drying interval, in which the air enters for 4 hours from the left-hand side of the dryer, the drying rate is clearly higher for the tray that is close to the air inlet. The drying rate of the other trays is promptly reversed in respect to those above presented.

This phenomenon of drying rate inversion was repeated each time the airflow was inverted, causing finally the moisture content convergence to the same value for all three trays. After a further investigation, no significant variations in product moisture content and quality, between trays taken from other parts of the dryer, have been observed. In this way a uniform product quality has been reached for all trays of the dryer and no additional redrying of all or part of the dried product was necessary.

5. Mathematical modeling

The drying kinetics was approximated using the Page (1949) thin-layer drying equation:

$$M(t)/M_0 = MR = \exp(-k \cdot t^n) \qquad (1)$$

with k and n being drying air temperature and moisture depended parameters. [6]

The above equation has been linearized by applying logarithms as:

$$\ln\left(-\ln\left(MR\right)\right) = n \cdot \ln t + \ln k \qquad (2)$$

and the k and n drying constants has been successfully obtained by plotting on a ln(-ln(*MR*)) versus ln*t* diagram. The curve, in view of Eq. (2), resulting in a straight line and the slope of the line determines the drying coefficient n while the intercept equals lnk. In Fig. 5, the family of lines obtained on a logarithmic plot for the different scenarios **a.** and **b.** are shown. The values of the drying coefficients n and k yielded are presented in table 1 below.

Table 1: The values of the drying coefficients n and k obtained for the two scenarios.

	Constant flow direction		**Alternating flow direction**	
	k	**n**	**k**	**n**
Right	0.079	1.1331	0.0864	0.9866
Middle	0.0474	1.2366	0.0651	1.0666
Left	0.036	1.2448	0.04113	1.2919

As can be clearly seen from the above presented graphs and table, the three curves approximating the constant flow direction scenario are equidistant and nearly parallel (the slopes are similar, with n~1.2). On the contrary, the curves approximating the alternating flow direction scenario, although starting as nearly parallel, at the end of drying tend to converge to the same value (around n~1), a fact that demonstrates the independence of the drying process from temperature.

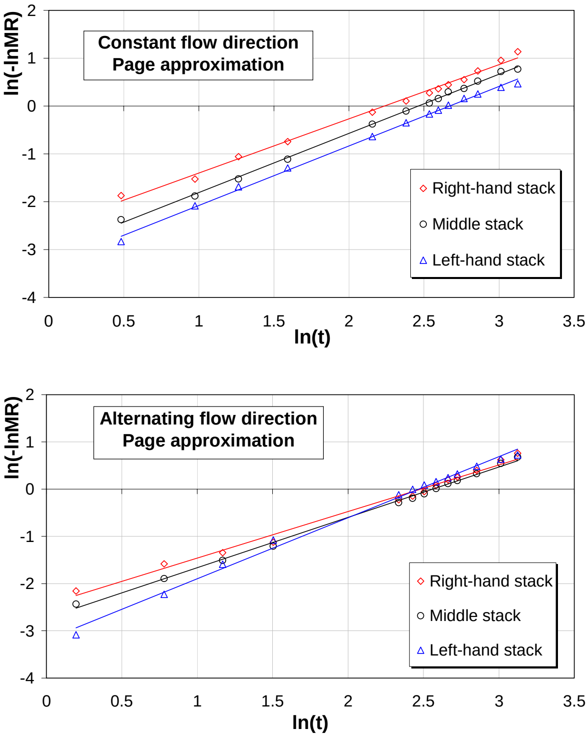

Fig 5: Page approximation of the drying curves for the investigated scenarios

6. Conclusions

After the investigation and practice of the dryer, adopting the proposed concept of drying management, its validity and feasibility has been confirmed.

A comparison of the drying times required to obtain uniform moisture content for all batches investigated has been carried out and it was estimated that time (and therefore fuel) savings of more than 30% could be achieved when the alternating flow direction drying process was adopted.

Although the dryer installation cost was slightly higher, due mainly to the additional air duct work necessary to achieve the airflow inversion, this extra cost has been completely compensated by the improvement in product quality. It is evident that there was no additional cost of redrying the inadequately dried product, while no additional personnel for the wet product selection was required. Therefore the above-presented method of drying management offers serious advantages and has to be taken into consideration in the design of new drying plants.

The potential offered by this approach was thus demonstrated by means of energy and time savings, as well as by ensuring improved uniformity of the final product quality and of the moisture content.

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