Atmospheric freeze drying with heat pumps-
A new alternative for high quality dried food products

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Abstract

In the production of artificially dried food products to be used in dishes, soups and breakfast cereals, mainly two technologies are dominating the industrial production today. These technologies are direct heated driers operated at 60°C to 90°C and vacuum freeze drying operated below -30°C. Direct heated dryers have lower production costs than vacuum freeze dryers but with a much lower quality of the dried product. On the other hand, the vacuum freeze drying equipment high cost limits its use.

This paper presents atmospheric freeze drying with heat pumps as a new alternative for producing dried food products with high quality, which is similar as in vacuum freeze drying but with considerable lower production costs. The focus in the paper is on design, dimensioning and operation of atmospheric freeze dryers with heat pumps using combined drying mode with temperatures below and above the product freezing point.

The choice of drying temperatures, operating conditions, working fluids and systems of the heat pump will be discussed with respect to capacity, energy consumption and product quality. The product quality is affected by the selection of the drying temperature. Different food products have been dried at temperatures below and above the product freezing point. Relevant quality parameters such as color, taste, density and rehydration ability can be controlled according to the drying conditions. A step-up drying temperature regime for cod, starting with temperature below the cod freezing point and with a final drying at 20°C resulted in improved quality. Typically, the longer the initial residence time at atmospheric freeze drying implies reduced product shrinkage and increased the rehydration ability.

The interaction between the drying air side of the plant and the heat pump is studied with respect to the dryer thermal efficiency and heat pump coefficient of performance. Depending on the drying time at atmospheric freeze drying the energy consumption is best defined by the specific moisture extraction rate (SMER). Typical SMER values for atmospheric freeze drying with heat pumps are in the range of 4.6 to 1.5 kg of water per kWh when the initial residence time at atmospheric freeze drying changes from 0 to 10 hours in a step up drying regime.

1. ADIABATIC HEAT PUMP DRYERS

The conditions in a heat pump dryer can be controlled and favors its application to heat sensitive materials. This technology has been recently industrialized with applications in drying of fruits, vegetables, fish, dairy, biological and other materials. The drying mode at temperature bellow the material freezing point allow to adjust the product properties as indicated by results on color, hardness, porosity, density, rehydration and improved flavor or aroma. Figure 1 shows the main components of this dryer that has two independent heat pump and drying circuits that are integrated in the system by properly placing the components in the loops. The heat exchangers are the main devices for transport of energy and mass between the drying and heat pump loops.

Among this dryer's advantages are a high final product quality since the drying conditions can be regulated with drying temperatures from –20°C to 110°C. Property and quality parameters of the product can be controlled by using temperatures below the material freezing points or by partly freeze and above freezing drying modes.

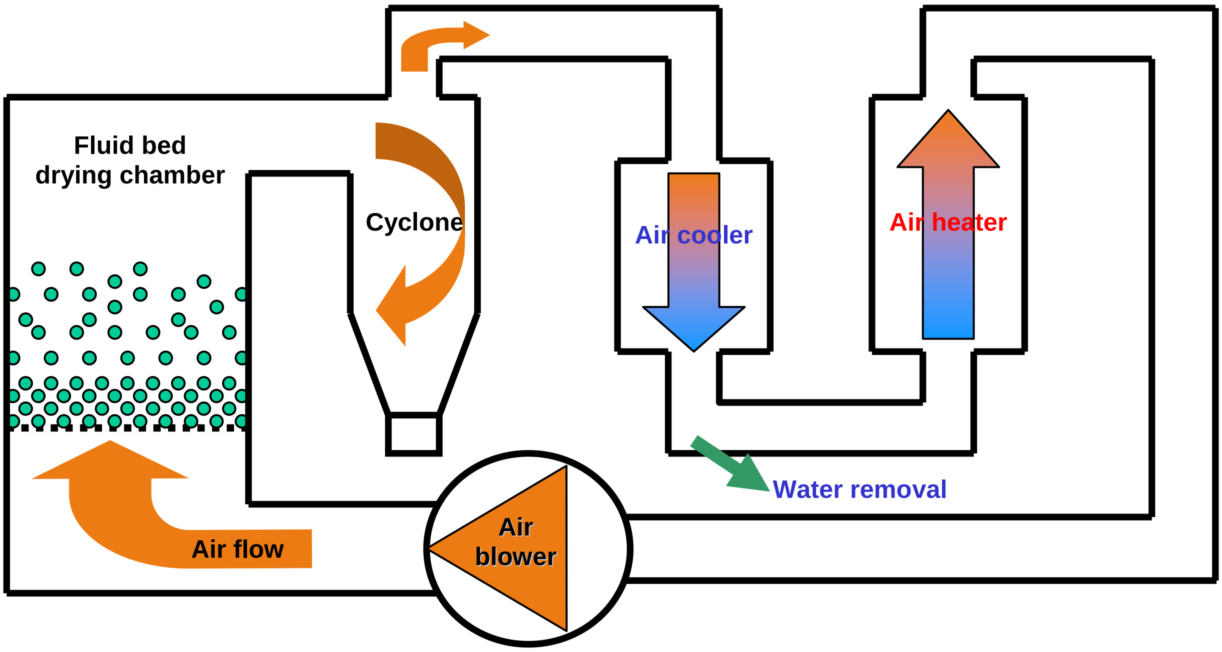


Figure 1. The fluidized bed heat pump dryer

Figure 1 and 2 shows the new heat pump dryer with air and heat pump circuit. The heat pump dryer is built to handle raw materials in different phases such as unfrozen or frozen granules, liquids, solution and foams. All drying circuit is made of stainless steel for easy cleaning and it has CIP and may be sterilized with steam or other solution at 2.2 bars.

In the drying circuit the air is cooled in the evaporator and the condensed moisture is drained. The energy is recovered as water vapor condenses in evaporator to reheat the air flowing through the gas-cooler.

The favorable aspect of the dryer is an environmentally friendly technology due to the recirculation of the drying air to avoid air exhaust with fine particles. Also the dryer can be designed to attain both high dryer thermal efficiency and high coefficient of performance, COP. The combination of the parameters defines the specific moisture removal ratio, SMER. A properly designed heat pump dryer has SMER up to 4.6 kg of water per kWh. The SMER is given by

$$\mathrm{SMER} \equiv \mathrm{COP} \cdot \frac{\Delta x}{\Delta h} \tag{1}$$

where the COP is expressed by

$$\mathrm{COP} \equiv \frac{Q_o}{W} \tag{2}$$

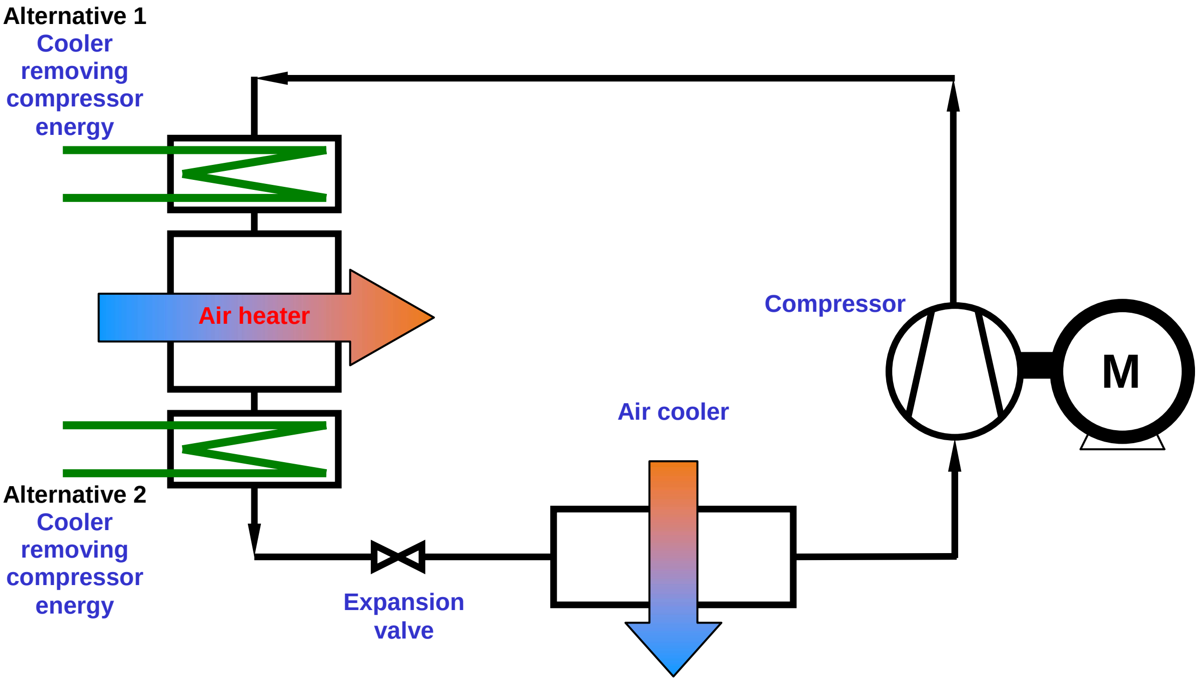


Figure 2. Linking the air and heat pump circuits in the fluidized bed dryer

2. CHARACTERISTICS OF ATMOSPHERIC FREEZE DRYING

Normally, a food product undergoing atmospheric freeze drying (AFD) has a freezing point depression due to reduction in solvent fraction while increasing the solute concentration. An additional effect due to reduction of moisture during drying is a continuous drop in the material latent heat of freezing.

The phase transition diagram phenomena may be graphically represented by plotting the experimental data on enthalpy as function of temperature and moisture content as obtained for apples by Alves-Filho (1996). Figure 3 show the family curves and indicates a clockwise shift for enthalpy as function of temperature and moisture content. The enthalpy-temperature shift occurs simultaneously as apple moisture changes from wet condition at 87%wb (blue) to intermediate moisture (black) and, finally, to semi-dried moisture of 37%wb (red). This moisture is the critical level in which the drying temperature can be raised without collapse due to a more stable structure at this solid fraction.

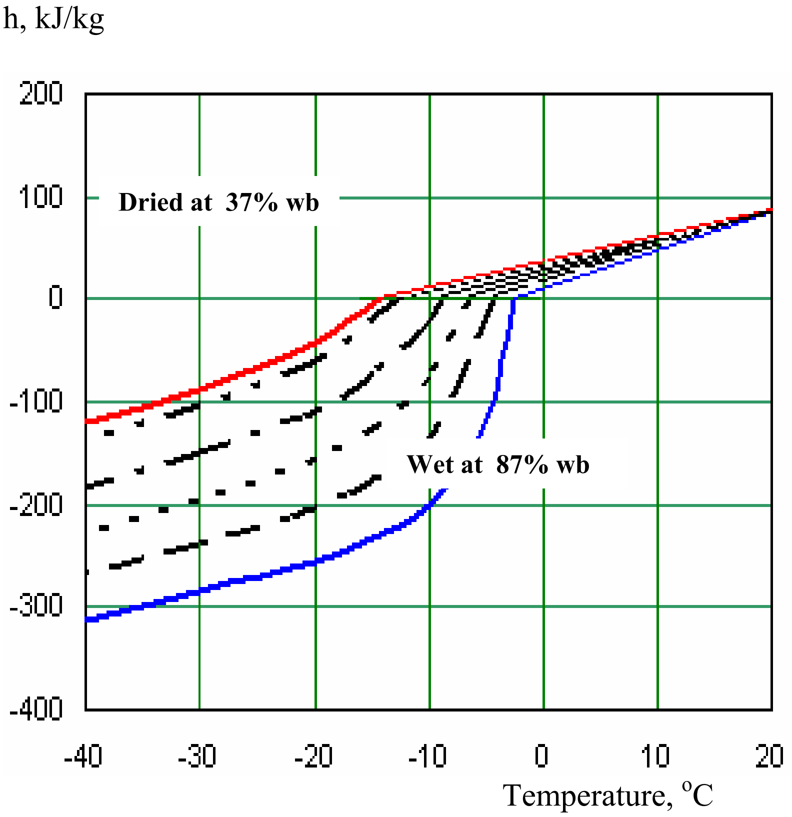


Figure 3. Apples' enthalpy as function of temperature and moisture content. The moisture changes from 87%wb (blue), to intermediate moisture (black) and to dried at 37%wb (red).

Therefore, this kind of experimental data contains information related to water mobility. Also, the enthalpy curves defines different phase zones, in which water is present in the porous food material.

The diagram in Figure 4 defines three regions each having different water mobility. It shows the zones in which the water phase is frozen, partly frozen or liquid. Water is in liquid phase in the zone A and drying is done by atmospheric drying (AD). In zone B the water fraction is partially frozen and drying is performed by atmospheric partial freeze drying (PAFD) and the in zone C the water is in frozen phase and drying is done either by atmospheric freeze drying (AFD). The water has highest and lowest mobility in liquid phase in zone A and frozen phase in Zone C, respectively. By analogy, water in the partially unfrozen water phase in Zone B has an intermediate mobility.

3. Modeling of freezing point depression of apples.

A wet material has fractions of solute and water that interacts and changes progressively with the drying process. As described previously the water fraction is retained with mobility more or less restricted by binding forces that depend on temperature, moisture content and structure.

AFD operation requires knowledge and prediction of product enthalpy, specific heats and freeze point temperatures.

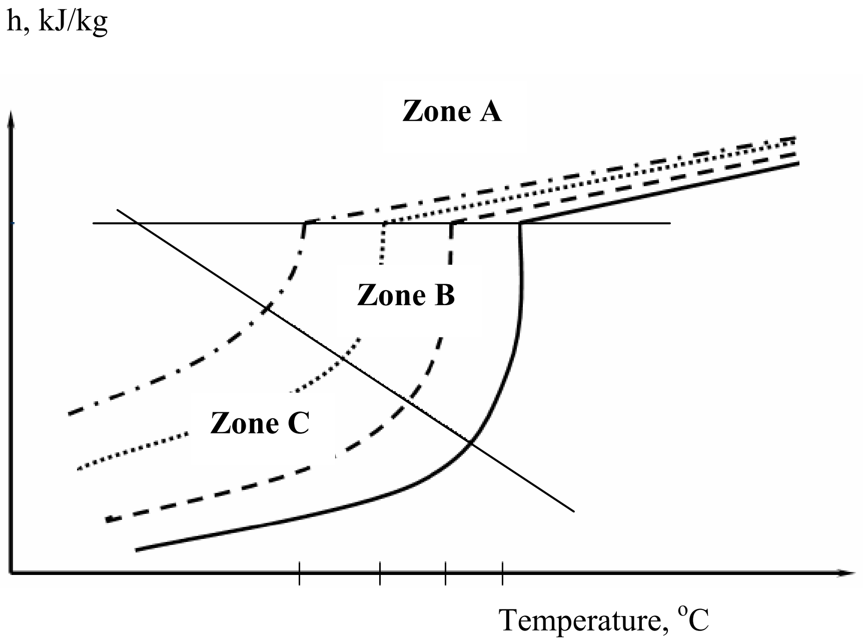


Figure 4. Proposed diagram to define the phase zones for the water fraction for a food material undergoing atmospheric freeze drying. Zone A: evaporation only, Zone B: evaporation and sublimation Zone C: sublimation only. Plots based on curves of enthalpy as function of temperature and moisture content for apple.

This is because the drying operation may be hampered at any stage of drying due to unwanted rise in temperature and consequent phase change causing structural collapse or increasing stickiness. Also, the product property depends upon the process-product temperature and moisture history during drying. Therefore, it becomes vital in controlling AFD to obtain a model for reliable prediction of the material freezing point depression during drying. The enthalpy family curves have been reported by Alves-Filho (1996) in terms of either moisture or solid fractions and moisture content, based on extensive experimental data obtained for apples and fruits. This available data can be fitted by a number of equations one of which is the expression suggested by Schwartzberg (1976).

The on-set freezing point temperature depression is due to changes in the material water and solids composition during different stages of AFD. Combined with relevant trial data, the drying temperature and water-solids fraction relationship provides the appropriate operation parameters to control AFD. It provides information to understand the process principles to produce stable and high quality powders without structural collapse or melting.

AFD can be combined with medium temperature to increase drying rate and reduce drying time. This is done when the moisture or solid fraction level is such that no significant solvent is mobile and no shrinkage occurs since it depletes product quality.

The material solid fraction for the change is such that the structure is stable due to relatively quick formation of a surface layer that is sufficiently dried and non-sticky as to form agglomerates. This is in agreement with studies on effect of initial water-solid fractions on shrinkage, from which the results indicate that the structural collapse is increases as the material solid fraction increases.

Table 1. Statistics to verify how well the regression equation represents the set of data form experiments on freezing point depression.

Statistics	**Indication**	**Statistics Values for ΔT**	**Statistics values for w_s**
Data points	Number of data	7	7
Average	Location of distribution balance	0.233	3.397
Variance	Spread of data around average	0.041	5.008
Standard deviation	Spread with the same unit as ΔT	0.202	2.238
Det./corr coeffs	Goodness of fit	0.9998/1.000	
Intercept – 1	B	-0.179	
Regression slope * K	E	199.242	

The experimental data for apples was used to correlate the moisture content with the freezing point depression during low temperature drying. Thus, the equation proposed by Schwartzberg is modified to describe the apple's solid fractions as function freezing temperature as follows

$$\frac{1}{w_S} = (1+B) + \frac{E}{M_W \cdot \left(1 - \frac{\Delta Ho}{RT_O}\right)} \cdot \left(\frac{1}{To - T}\right) \tag{3}$$

Let the constant K be defined as

$$K = M_W \cdot \left(1 - \frac{\Delta Ho}{RT_O}\right) \tag{4}$$

Substitution of K into Equation (1) yields

$$\frac{1}{w_S} = (1+B) + \frac{E}{K}\left(\frac{1}{T_O - T}\right) \tag{5}$$

where K is found by Equation (4) using pure water as a reference and considering its molecular weight, temperature and energy due to phase change.

Based on Equations (3) and (5) and the experimental data for apples, the correlation equation was found and it is plotted in Figure (5). It shows a highly linear correction between the inverse of solids fraction and the inverse of the temperature difference.

They are related to constants are B and E and are specific for each food product. Using the regression equation and the apple's experimental data points the constants are determined as B=-0179 kg/kg and E=199.242 kg/kg.K.

The correlation's intercept and slope are given in Table 1 as well as the statistics to explain how well the regression describes the experimental data. The determination coefficient is 0.9998 and indicates a very strong nearly perfect correlation between dependent and independent variables. Further it shows that the equation fully overlaps all data points and the correlation is also positive or that $1/w_S$ rises as 1/(To-T) increases.

The coefficient of determination represents the fluctuations between independent and dependent variables. It indicates the proportion of total variation that is explained by the regression line. The calculated was $r^2 = 1.000$ and means that 100% of the total variation in

$1/w_s$ is due to the linear relationship with 1/(To-T), or, that zero % is due to unexplained variation.

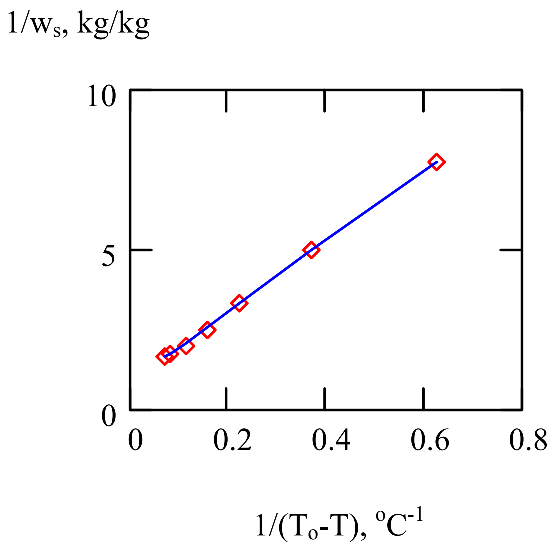


Figure 5. The inverse of moisture content versus 1/ΔT for apples. Experimental data points (diamonds) and continuous straight line obtained by regression using Equations (1) and (3).

Figure 6 shows the moisture content in wet and dry basis as function initial freezing point for apples. For comparison purposes it shows also the experimental data points for solids fraction (squares) and moisture (circles) and the continuous lines as predicted from regression line constants using Equation (3). Consistently with the statistics, the plot shows an excellent agreement between the experimental and predicted values.

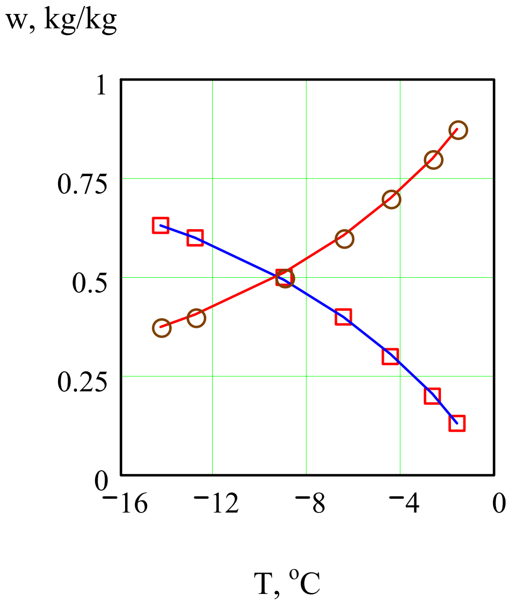


Figure 6. Apples' experimental data points for solids fraction (squares) and moisture fraction (circles) and predicted continuous lines using Equation (3) and the regression constants.

4. DESIGN OF HEAT PUMP DRYING IN COMBINED TEMPERATURE MODES

Heat pump drying allows operation in combined modes using air temperature below and above the material freezing point. To achieve as high SMER as possible an industrial fluidized bed heat pump dryer should be designed according to the following "rules":

- Drying operation with optimum bed height to attain a higher relative humidity at the dryer outlet
- Stable fluidization due to the sorption characteristics of the material being dried
- Continuous, not batch operation, due to the lowering of capacity and efficiency during a batch process
- As high inlet temperature in the dryer as possible, due to improved thermal efficiency and capacity
- As low refrigeration capacity as possible, as long as the desired production is achieved (over-sizing increases dh/dx and reduces SMER)
- The choice of evaporating and condensing g temperature of the heat pump should be the combination giving the best combination of COP and dh/dx (an optimum might exist).

The energy consumption in an a continuous heat pump drying operated in a combined drying mode at temperatures at –5°C in the first stages and at 30°C at the second stage. The SMER is calculated modifying Equation (1) as follows

$$SMER = (COP_{LT}/(dh/dx)_{LT})*(\tau_{LT}/\ \tau_{tot}) + (COP_{HT}/(dh/dx)_{HT})*(\tau_{HT}/\ \tau_{tot}) \quad (6)$$

The conditions above are given in Table (2) and the process state points can be easily drawn the moist-air Mollier diagram.

Table 2. Process conditions for the heat pump drying in combined mode

Air and heat pump loops	**LT**	**HT**
Air inlet drying temperature	-5 °C	30 °C
Air inlet relative humidity	40%	40%
Air outlet relative humidity	80%	80%
Surface temperature of air cooler	t_{dp} - 5°C	t_{dp} - 5°C
Heat pump evaporating temperature	air cooler surface temperature – 2°C	air cooler surface temperature – 2°C
Heat pump condensing temperature	air inlet drying temperature + 5°C	air inlet drying temperature + 5°C
Heat pump refrigerant	NH_3	NH_3

The calculations are plotted in the Figures 7 and 8, which indicate that drying at –5°C for 10 hours results in lower bulk density, higher rehydration ability and energy consumption 7.5 times higher than drying at 30°C only.

The SMER for the combined drying mode with 10 hours at –5°C reduces the SMER to 67% compared with drying at 30°C.

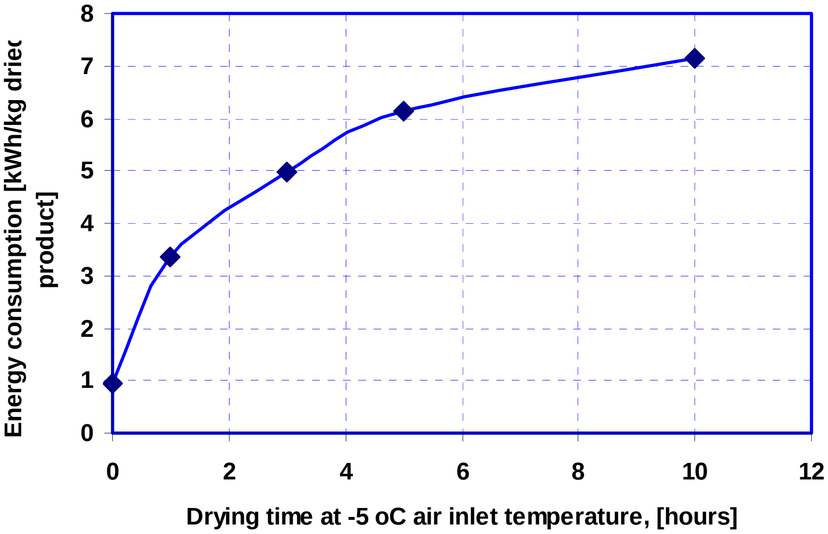


Figure 7. Dryer energy consumption per kg dried cod with increasing time at low temperature

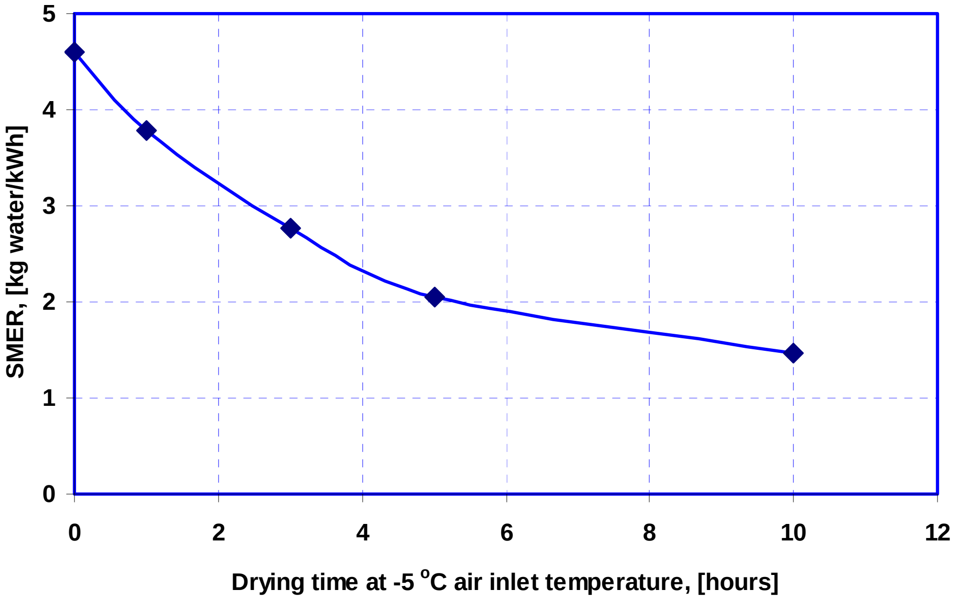


Figure 8. SMER for dried cod pieces with increasing drying time at low temperature

6 PROPERTIES AND QUALITY OF ATMOSPHERIC FREEZE DRIED PRODUCTS

The quality of atmospheric freeze dried cod is affected by the drying conditions, especially the drying air temperature. The bulk density, re-hydration, ability and color for cod cubes is affected by different temperatures and residence times at temperatures below the material freezing point as shown in Figures 9, 10 and 11.

ρ, kg/m^3

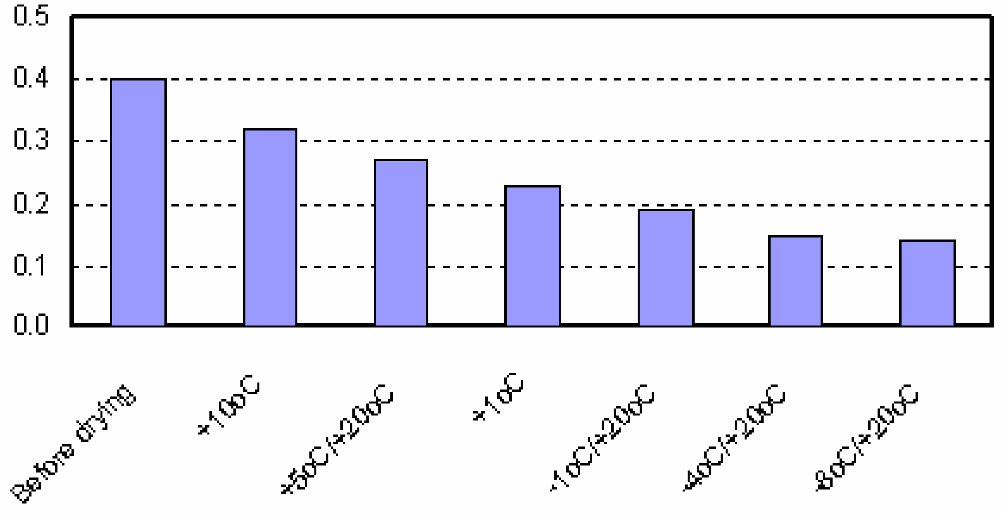
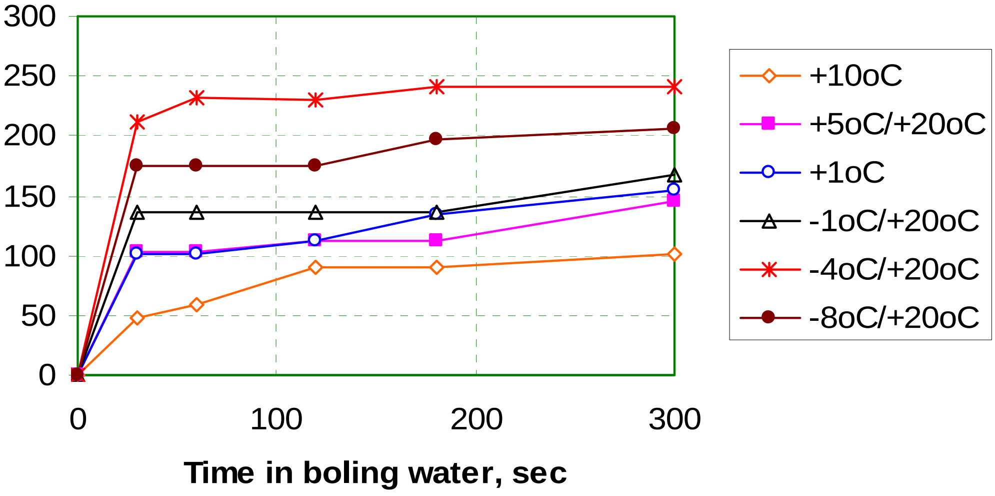


Figure 9. Bulk density of cod cubes dried at different temperature-time programs.

Ra, %



Time in boiling water, sec

Figure 10. Rehydration of cod cubes dried at different temperature-time programs.

The plots clear indicate that the cod samples present lower bulk densities, higher rehydration and lighter color when dried at lower the temperature and longer residence time at freeze drying conditions.

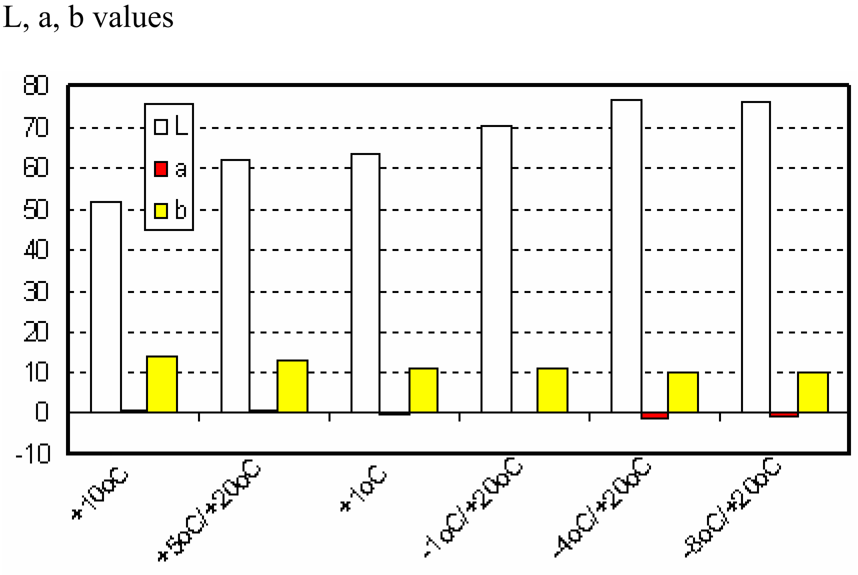


Figure11. Color measurements of cod cubes dried at different temperature-time programs.

8. CONCLUSIONS

Atmospheric freeze drying with heat pumps is a new alternative for producing high quality dried food products with low density, high re-hydration ability and light color. By controlling drying conditions these properties can be adjusted. **C**ompared to vacuum freeze drying atmospheric freeze drying is considerably cheaper and this drying process is now very industrialized in Hungary for drying of sweet corn and green peas.

A model to determine the solid fractions as function of moisture content and freezing point depression is proposed. The drying kinetics of atmospheric freeze drying of cod in a tunnel dryer and calculation of SMER depends on the residence time in freeze drying conditions. With an initial drying time period of 10 hours at -5 °C, the SMER reduces to 67% compared to 30°C only. The energy consumption is 7.5 times higher compared to drying at 30°C only.

9. STATISTICS FOR THE REGRESSION ON FREEZING POINT DEPRESSION

Statistics is useful to verify how well the regression fits the set of data on freezing point depression. Then, let $y=1/w_s$ and $x= 1/(To-T)$, the average is found by

$$\bar{y} = \frac{\sum_{i=1}^{n}(y)}{n}$$

The most common formula for computing a sample variance is:

$$s^2 = \frac{\sum_{i=1}^{n}(\bar{y}-y)^2}{n-1}$$

The sample standard deviation the square root of the variance and given by

$$s = \sqrt{\frac{\sum_{i=1}^{n}(\bar{y}-y)^2}{n-1}}$$

The correlation coefficient and the coefficient of determination are calculated by

$$r = \frac{n\cdot\sum(xy)-\left(\sum y\right)\cdot\left(\sum x\right)}{\sqrt{n\cdot\left[\left(\sum y^2\right)-\left(\sum y\right)^2\right]}\cdot\sqrt{n\cdot\left[\left(\sum x^2\right)-\left(\sum x\right)^2\right]}}$$

$$r^2 = \frac{\sqrt{\sum(xy)-\left(\sum y\right)\cdot\left(\sum x\right)}}{n\cdot\left[\left(\sum y^2\right)-\left(\sum y\right)^2\right]\cdot\left[\left(\sum x^2\right)-\left(\sum x\right)^2\right]}$$

10. NOTATIONS

w_s	mass fraction of solids, kg/kg
B	mass constant, kg/kg
E	mass-temperature constant, kg/kg.K
T_o	freezing temperature of pure water, K
T	initial freezing point for apple at with mass fraction of solids w_s, K
M_w	molecular weight of water, kg/kmol
ΔH_0	latent heat of freezing pure water, kJ/kg
y	defined as 1/ws
x	defined as 1/(To-T)
s	standard deviation
s^2	variance
Ra	rehydration ability, %
R	universal gas constant, kJ/kmol.K
r	correlation coefficient
r^2	coefficient of determination
ρ	bulk density, kg/m^3

11. REFERENCES

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