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ADVANTAGES OF DRYING OF VEGETABLES USING THE INTEGRATED HEAT PUMP TECHNOLOGY

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Abstract: The world is facing an increase in human population and consequently need to produce more fresh and dried products for this expanding population. New technologies should fulfill the objective of economical profitability, which is mostly dependable on energy efficiency due to the trend of increasing energy cost. Currently, as a drying process consumes up to 50% of the total amount of energy used in industrial purposes. One of the relatively new technologies for these requirements is heat pump drying (HPD). In this work a laboratory heat pump drying is applied for vegetables drying. The drying of vegetables was conducted in fluidized bed. Fluidized bed gives important advantages such as good solid mixing, high rates of heat and mass transfer and easy movement of materials. The air drying was adjusted on temperature regimes of 45°C and 15°C with three relative humidity levels. Some of the limitations in fluidized bed drying application are high pressure drop and high electrical power consumption. The results have shown that higher temperatures increase the rate of moisture removal from the vegetables (green peas). Difference in relative humidity of the air drying plays an important role in the process.

Keywords: drying, heat pump, vegetables, fluidized bed

1. INTRODUCTION

This work covers the experiments and modeling green peas drying on a pilot scale heat pump dryer. Focus will be given on the effect of heat pump operating conditions, drying temperature and relative humidity on kinetics and on the dried product's characteristics. Heat pump dryers have been known to be energy efficient when used in conjunction with drying operations. The principal advantage of heat pump dryers emerge from the ability of the heat pumps to recover energy from the exhaust gas as well as their ability to control the drying gas temperature and humidity. Many researchers have demonstrated the importance of producing a range of precise drying conditions to dry a wide range of products and improve their quality. The main components of the single stage heat pump system are the expansion valve, evaporator, internal and external condenser and compressor as illustrated in figure 1.

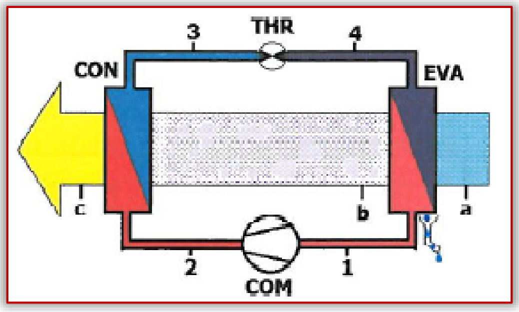

Figure 1. Principle of operation in a simplified heat pump dryer

After flowing through the evaporator and condenser of the heat pump the dry and warm air is ready to flow into the drying chamber in which the material, which is to be processed, is being placed. The simplified heat pump dryer has two separated loops with common heat exchangers. The drying air loop (*abcd*) contains the air cooler (*EVA*), heater (*CON*), blower and drying chamber. The refrigerant loop (*12341*) main components are the expansion valve (*THR*), evaporator (*EVA*), condenser (*CON*) and a compressor (*COM*). The fluid of the heat pump and drying air loops are coupled through the common evaporator and condenser to recover the exhaust energy.

2. PRINCIPLE OF HEAT PUMP DRYING

Figure 2 illustrates the isentropic and non-isentropic saturated vapor compression heat pumps with dry expansion evaporator and drying channels.

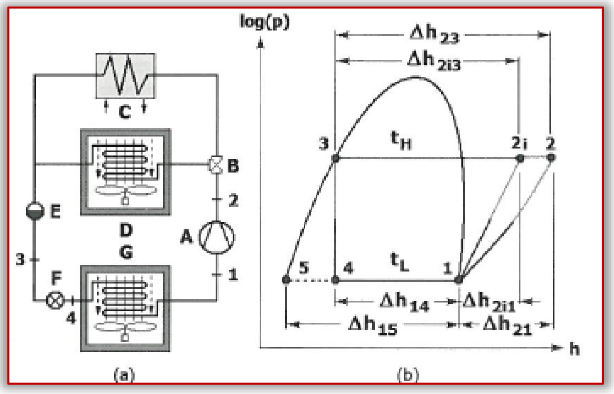

Figure 2. The isentropic and non-isentropic saturated vapour compression heat pumps indicating the corresponding specific enthalpy differences in each process

Figure 2a shows the main components: A – compressor, B – three way valve, C – external condenser, D – drying channel with air heater, E – liquid receiver, F – expansion valve, G – drying channel with air cooler. Also, Figures 2a and 2b show the layout and the state points in the cycles in a log pressure versus enthalpy diagram, respectively. From state point 1 the saturated vapor is isentropic and non-isentropic compressed to super-heated vapor to points 2_i and 2, respectively. Then, the vapor flows through the condensers changes phase to saturated liquid and is collected in the receiver. The saturated liquid leaves the receiver at point 3 and it is throttled to a liquid and vapor mixture at point 4. Then, the mixture flows through the evaporator and becomes saturated vapor at point 1 to be compressed again.

3. FLUIDIZED BED AND PRODUCT QUALITY

Fluidized bed dryers (FBD) are used extensively for the drying of wet particulate and granular materials that can be fluidized, and even slurries, pastes, and suspensions that can be fluidized in beds of inert solids. They are commonly used in processing many products such as chemicals, carbohydrates, foodstuff, biomaterials, beverage products, ceramics, pharmaceuticals in powder or agglomerated form, healthcare products, pesticides and agrochemicals, dyestuffs and pigments, detergents and surface-active agents, fertilizers, polymer and resins, tannins, products for calcination, combustion, incineration, waste management processes, and environmental protection processes. Fluidized bed operation gives important advantages such as good solid mixing, high rates of heat and mass transfer, and easy material transport.

Some advantages of fluidized bed drying are the high rate of moisture removal, high thermal efficiency, ease of control and low maintenance cost. The high rate of moisture removal is due to the large interfacial surface area which is in order of 3000 to 45000 m^2/m^3 in the fluidized bed. This is also the reason for very high rates of heat transfer achieved in fluidized beds.

Some of the limitations in drying application of the fluidization are high pressure drop and high electrical power consumption for the blower. Also the drying product may be damaged in intensive fluidization or particle to particle and particle to wall collisions.

Experimental design

The experiments were conducted in a heat pump drying system with a fluidized bed. Each batch of raw material placed inside the drying chamber had a mass of 1000 grams. The green peas samples were dried at three values of drying air temperature and three values for the relative humidity. The temperatures were 45°C and 15°C and each temperature was fixed tested at relative humidity of 60%, 40% and 20% with exception of 45°C as previously mentioned. This resulted in a design of eight drying tests. The details of experimental conditions and setup for all eight tests are presented in Table 1.

Table 1. Experimental conditions and setup
for all heat pump drying tests

Test Number	Temperature, [°C]	Relative humidity, [%]
1.	45	40
2.	45	20
6.	15	60
7.	15	40
8.	15	20

The frozen green peas were mixed and homogenized to form a large batch that was partitioned into eight uniform batches of green peas to be dried according to the mentioned design. One drying test took 3 hours to complete. During the drying of all tests the drying chamber was taken out every 20 minutes period to measure the change in mass. Relatively small masses of dried product samples were also extracted at every 60 minute interval, which makes 3 extractions every test. The extracted material was put in small vessels whose mass was determined previously, and then the total mass of vessel with extracted sample was measured, after which they were put into preheated oven for 24 hour drying period. The drying oven was set at a temperature of 105°C and for 24 hours. The already known mass of the empty vessel and total mass of vessel with the product allows us to calculate the mass of extracted product. The product was dried in the fluidized bed with the air velocity kept at approximately 1 m/s.

The drying chamber and supporting cabinet

The drying chamber is placed inside the isolated wooden cabinet made of plywood with styro foam insulation. The cabinet's dimensions are 0.8x0.8m in cross section with height of 1.5m.The drying chamber is made of plexiglas and it is easily locked and unlocked in central base positioned within the cabinet using a three pin lock-rotation mechanisms. The chamber is inserted in the drying loop but separated from outdoors by a sampling access door located in the front of the cabinet. The door is opened and closed using two external locks. There are two inlet and outlet tubes connecting the cabinet and chamber to the drying loop. The inlet tube is connected to the central base of the cabinet and to the cylindrical chamber containing the green peas. The chamber exhaust flows through the outlet tube that is positioned at the upper part of the cabinet. During the process of moisture removal the green peas contained in the cylindrical chamber is in a fluidized by controlled air flow. The density was measured based on standard determination of both mass and volume.

4. ANALYSIS OF DATA AND MEASUREMENTS

Water content

The water content of the green peas sample is defined either on a wet or on dry basis.

The moisture content in wet basis is calculated using the equation:

$$w_{wb} = \frac{m_w}{m_t} = \frac{m_t - m_d}{m_t}$$

The moisture content on dry basis w_{db} is calculated by dividing the mass of water m_w in green peas sample with mass of dry-matter md as shown in equation:

$$w_{db} = \frac{m_w}{m_d}$$

The bulk density

We have used both the density of individual particles and the density of the bulk material, which also includes the air spaces between the particles. The latter measure is termed the bulk density and it is the mass of solids divided by the bulk volume as expressed through the equation:

$$\rho_b = \frac{m}{V}$$

The particle density

To obtain the particle density from each test samples of ten individual green peas were taken and the diameters were measured using a caliper with accuracy to 1/20mm.

Similarly the particle density is obtained using ratio of the average mass of ten particles and average volume of same particles and it is expressed by equation:

$$\rho_p = \frac{\bar{m}}{\bar{V}}$$

5. RESULTS AND DISCUSSIONS

Drying Kinetics

Table 2 shows the values of moisture content on dry basis calculated for tests 1 and 2 done with temperature of 45°C and relative humidity of 40% and 20%. The development of moisture content on dry basis follows the kinetic measurements at time intervals of 20 minutes over a period of three hours. It is obvious that test 2 with the lowest relative humidity is the one with the lowest moisture content after this drying time. The experimental data for these tests are plotted in Figure 3.

Table 2 Experimental conditions and setup
for all heat pump drying tests

	Moisture content on dry basis [%]	
Elapsed time [min]	Test 1	Test 2
0	323.19	323.19
20	180.58	170.84
40	119.64	114.6
60	84.34	81.76
80	63.06	61.57
100	49.77	48.88
120	40.88	40.12
140	34.66	33.6
160	30.17	29.5
180	26.66	24.8

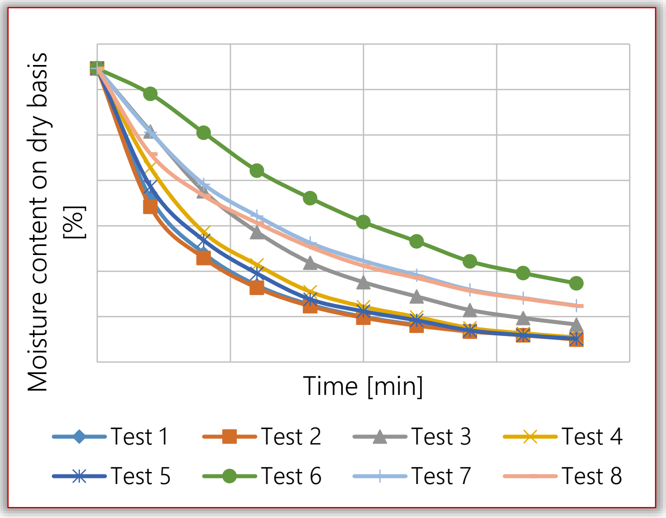

Figure 3. Development of moisture content
on dry basis for all tests

Table 3 shows the development of moisture content on dry basis for tests 6, 7 and 8 done with temperature of 15°C and relative humidity of 60%, 40% and 20%. Test number 8 is the one with lowest moisture content and it is the same test in which the drying air had the lowest relative humidity. The experimental data for these tests are plotted and presented in Figure 3.

Table 3. Development of moisture content
on dry basis for tests 6, 7 and 8

	Moisture content on dry basis [%]		
Elapsed time [min]	Test 6	Test 7	Test 8
0	323.19	323.19	323.19
20	295.13	252.98	229.07
40	252.43	195.68	183.16
60	210.71	160.85	153.15
80	180.45	131.19	126.62
100	154.08	111.38	106.01
120	132.84	95.68	92.64
140	110.92	79.73	78.42
160	97.93	70.46	69.83
180	86.67	62.21	61.96

6. CONCLUSIONS

Advantages:

- Heat pump drying (HPD) offers one of the highest specific moisture extraction ratio (SMER), often in range of 1.0 to 4.0, since heat can be recovered from moisture-laden air.
- Heat pump dryers can significantly improve product quality by drying on low temperatures. At low temperatures, the drying potential of the air can be maintained by further reduction of the air humidity.
- A wide range of drying conditions typically -20°C to 100°C (with auxiliary heating) and relative humidity 15 to 80% (with humidification system) can be generated.
- Excellent control of the environment for high value products and reduced electrical energy consumption for low-value products.

This work focus on heat pump drying of green peas at varying conditions. The results have shown that the temperature of the drying air has the highest influence on products moisture content. There is also a significant influence of the relative humidity of the drying air on the final product's moisture content.

We can see that the tests with 45°C inlet air have faster moisture removal but also that Test 4 and Test 5 with 35°C inlet air 40% and 20% of relative humidity is approaching the value of the test 1. On the other hand the set of tests with 15°C have high values of moisture content and it is obvious that for that low temperature not even changes in relative humidity can increase moisture removal rate.

Overall, test 2 produced the dried green peas with lowest moisture content. In terms of color a higher temperature regime influenced the most drastic change in the color properties of the final product but still the values remained relatively close between tests. The biggest difference that can be noticed is the similarity of values for Test 1 to Test 4, and also the similarity in results of color for Test 5 to Test 8.

Note

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