SZENT ISTVÁN UNIVERSITY

DEWATERING PROPERTIES OF BIOLOGICAL MATERIALS DURING MICROWAVE TREATMENT

Thesis of PhD work

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Gödöllő, Hungary

2016

Doctoral school Denomination:	Mechanical Engineering Doctoral School
Science:	Agricultural Engineering
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1. INTRODUCTION, OBJECTIVES

Within agriculture, the operation of drying is one of the processes that require the largest amount of energy. In addition, agricultural drying is more complicated than the industrial one, as the process of reducing the moisture content of the living material entails morphologically determined biological changes. Therefore, in order to avoid the devastation of the product or the distortion of its tissue structure and also to optimize the energy level of the process, the parameters of the drying process must be chosen by scientific reasons. The energy consumption of the microwave drying process is of one order of magnitude lower than that of the convection processes, thus, using it in the drying of fruits or vegetables of high initial moisture content may have advantages.

The target of my research is to create a series of measure which results in being able to calculate the characteristic parameters of the processes of energy- and material transport, paying special attention to the ways of convection and the properties of drying.

I would like to examine the drying processes of such vegetables which have high initial moisture content, and whose morphological structures are different from each other. Thus, besides being able to characterize the drying parameters of each vegetable, the drying properties of plant groups can also be compared.

As one of the most important parameter of the drying processes is the efficiency of the energy supply, thus I would like to realize the experiments using several drying performances in order to specify the correspondence between energy consumption and efficiency.

To sum up the objectives of my experiment:

- to specify the drying properties of each vegetable at the applied microwave power level, and based on the data, to draw general conclusions on the properties of plant groups;
- to specify the impact of the amount of energy supply on the drying parameters e.g velocity of drying, energy consumption;
- to reveal the connection between the different morphological structures of the examined plant groups and their energy data during drying;
- to specify the characteristic phases of the microwave energy transfer process.

2. MATERIAL AND METHOD

The measuring methods and equipment are shown in this chapter. To determine the drying properties of each plant groups laboratory experiments were performed. The experiments took place in Heat engineering lab of the Szent István University, Faculty of Mechanical Engineering, Institute of Process Engineering.

2.1. Investigated plants

In my experiments I investigated two plant groups from agricultural products, which have high initial moisture content, but their morphological structures are noticeably different.

The Solenaceae group

- potato (*Solanum tuberosum*)
- tomato (*Lycopersicon esculentum*)
- paprika (*Capsicum annuum*)
- eggplant (*Solanum melongena*)

The Umbelliferae group

root vegetables

- celery (*Apium graveolens*)
- parsley (*Petroselinum crispum*)
- parsnip (*Pastinaca sativa*)
- carrot (*Daucus carota*)

leaf vegetables

- celery (*Apium graveolens*)
- parsley (*Petroselinum crispum*)
- dill (*Anethum graveolens*)

2.2. Measuring instrumentation

As measuring instrumentation, I used an equipment which had been developed for microwave drying experiments, whose relevant properties are as follows:

- 230 V/50 Hz current supply,
- standard 2.45 GHz operating frequency,
- continuously adjustable power level, ranging between 100 W and 700 W,
- directional couplers fitted to the resonator chamber for the permanent detection of the progressive waves (P_h) and the reflected waves (P_v) during the drying process,

- uniform distribution of electromagnetic field in the drying chamber,
- computer connection for the permanent data acquisition.

See Figure 1 for the configuration of the microwave drying and measuring equipment.

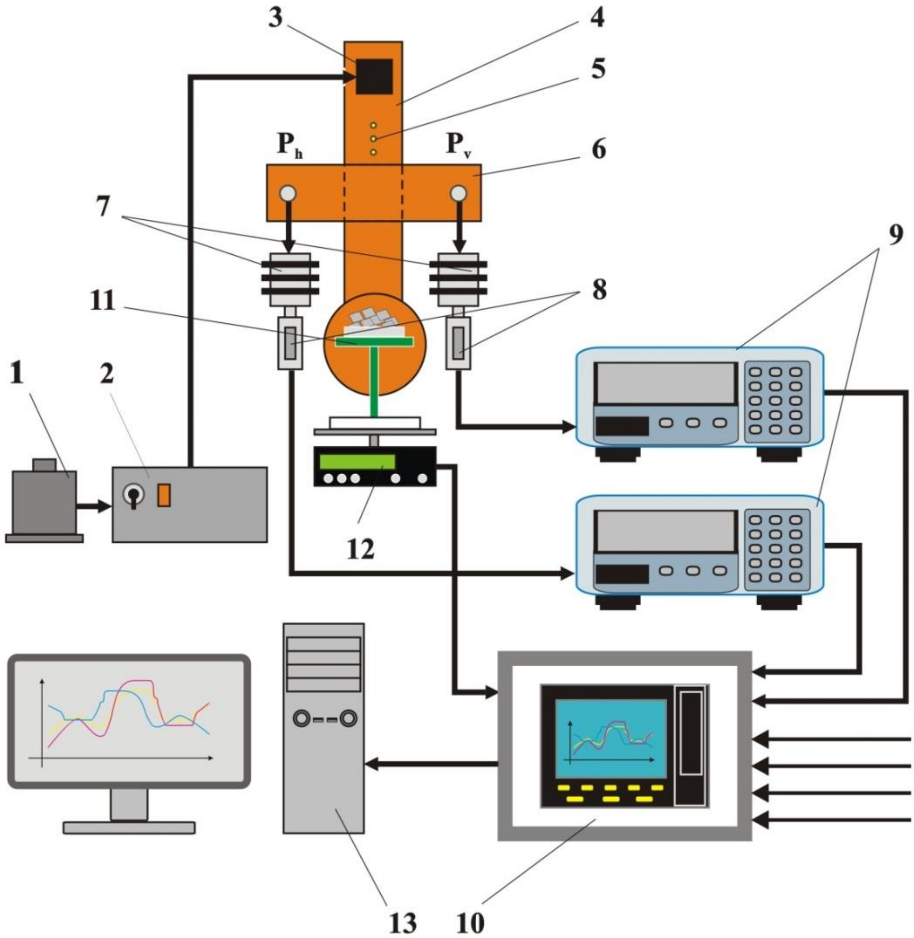

Figure 1. Microwave drying and measuring equipment

(1) toroid transformer, (2) transformer and switch unit, (3) magnetron (4) waveguide, (5) tuner probes, (6) measuring probes, (7) attenuators, (8) sensors for transmitted and reflected energy, (9) power meters, (10) data recorder, (11) sample holder, (12) scale, (13) PC

During the measurements, the first step is to calibrate the frequency level of the toroid transformer (1), which serves for adjusting the power of the magnetron. After the calibration, the magnetron (3) can be started by the master switch (2) located on the power supply unit. The microwave energy is transmitted to the operating space through the waveguide (4) whose cross section is rectangular. This pipe supply line is where tuner probes (5), which prevent harmful reflection in the direction of the magnetron, are located. The microwave performance caused by the transmitted waves (P_h) and the reflected waves (P_v) are detected separately by the coupling split (6) which is perpendicular to the pipe supply line. The coupling coefficient of the directional coupler is 28 dB. The performances following the directional coupler are still too high to be directed straight into the power measuring instruments, therefore, a fix 20 dB attenuator (7) is applied which must be connected forestall the performance measuring probe (8). The microwave performance is transformed into electric signs by the power meters (9) and the signs are recorded by a multichannel data recorder unit (10). The mass loss of the material located in the sample holder (11) is measured by an analytical scale (12) whose data are also recorded by the data recorder unit. I used temperature sensors to measure the temperatures of the laboratory, of the inflowing and outlet air of the operating space, and that of the cooling air of the magnetron. The data recorded by the data collector were analysed by me on a personal computer (13).

2.3. Sample preparation

The examined materials of agricultural origin have different morphological properties, so the preparation of the samples could not be the same. In order to be able to examine the dehydration properties of the different plant groups, the experiment had to be executed with the least deviation possible. Keeping in mind this target, during the preparation of the samples, I tried to maximize their size in 1 cm. In order to obtain a homogeneous sample range, always several plants were crushed.

2.3.1. Preparation of Solenaceae

Plants belonging to the *Solenaceae* group are approximately the same size, such as their crops, so their preparation was similar.

I made 1-cm- thick slices of the crops which were subdivided into cubes with an edge length of 1 cm. As the shape of the slices is influenced by the shape of the crop, the parts made from the outer slices were not perfect cubes, but I used them, too.

The crop of the paprika plant is a bit different from that of the other plants which show homogeneous crop structure. The crop of the paprika plant consists of a thick crop layer with an empty space and the core inside, therefore, in this case, I had to modify the preparation of the sample. First, I removed the core, then I cut 1-cm-thick longitudinal slices of the crop. Finally, I cut them into 1-cm-long pieces.

2.3.2. Preparation of root vegetables

The root vegetables, which belong to the Umbelliferae group, have similar morphological structure, therefore the process of sample preparation was the same. First, I removed the leaves of the plant, then I also cut the thin roots from the root part. I made 1-cm-thick slices of the remaining main root, which were subdivided into cubes with an edge length of 1 cm, if possible (if their diameter exceeded 1 cm). If the diameter was shorter than 1 cm, I did not cut the slice.

2.3.3. Preparation of leaf vegetables

The preparation of leaf vegetables was the same in the case of each plant. First, I removed the remained root parts, then I cut both the leaves and the petiole together into 1-cm-long pieces. I cut the large leaves (e.g. celery) vertically by the given dimension.

2.4. The measuring methods

During the experiments, I examined material samples prepared as described in 2.3. For the measurements, I used 105-mm-diameter Petri cups which fitted perfectly into the 125-mm-diameter operating space. I piled the material into the cups with no regular pattern, which made possible the secure (without the risk of falling or tipping out) piling of 80 g of Solenaceae or root vegetables, which can be characterized by a 0.25 space filling index, compared to the total volume of the microwave sample space. In the case of leaf vegetables, the maximum charge mass was 25 g, which can be characterized by a 0.51 space filling index.

The power levels that I applied to the masses of the samples and also the operating periods were determined by the results of my previous test measurements. As I wanted to execute the measurements at least at 3 power levels, thus during the experiments I adjusted the applied voltage of the toroid transformer to 140, 160 and 180 V. The magnetron power values that belong to each adjusted voltage value are shown in Chart 1.

Chart 1 Magnetron power values belonging to the adjustable toroid voltages

Voltage of the toroid transformer	Magnetron power
140 V	456.8 W
160V	523 W
180V	554.6 W

The operating period at the 456.8 W level - depending on the plant - ranges between 26 and 37 minutes, at the 523 W level between 18 and 22 minutes, while at the 554.6 W level between 12 and 14 minutes. Leaf vegetables were used only for checking purposes, so I used only the 523 W level for drying them with an 11-minute-long operation period in each case.

Each and every drying experiment was executed in the same way. First, I measured the previously established amount of sample, considering the plant, than I put it into the operating space. When the operating period ran out, I took the samples from the operating space, I put them in a dryer, and dried them to the balanced moisture content prescribed by the standards (ASAE S358, at a temperature of 103 °C, for 24 hours), then I measured them again. I executed each measurement adjustment 5 times. I recorded the performance data (progressive and reflected) in each measurement cycle every 5 seconds. The weight losses in the case of Solenaceae and root vegetables at the 456.8 W and 523 W levels were recorded by me every minute, while at the 554.6 W level and in the case of leaf vegetables every half minute. During the test measures, I experienced a minor degree of condensation, especially during the drying of high moisture content materials. To eliminate this effect, I put a ventilator to the end of the channel, which gave a 0.3 m/s air flow. It proved to be sufficient for the elimination of condensation, while it did not influence the enthalpy of the instreaming and outflowing air. Beside the temperature of the air, I recorded the temperature of the laboratory and - to be conductive to the secure operation of the device - the temperature of the cooling air of the magnetron, too. These data were collected every 5 seconds, too.

During analysing the measurement data, I determined the properties which are always applied during classical drying processes (moisture content, drying rate) and also the specific and relative properties, which make the characteristics of the certain plants or plant groups comparable from the point of view of energy consumption.

3. RESULTS

In this chapter, I sum up the results of the executed measurements, and enumerate statements based on my experience on the connection between microwave energy transfer and the morphological structure of the plants.

3.1. Results of microwave drying experiments

The series of data recorded during the microwave dryings were analysed by me in the same way in the case of each plant and I introduce them through the example of the parsnip.

3.1.1. Results of parsnip measurements

First, I drew the drying kinetic graph based on the results of the 5 measurements at the different performance levels. As each plant species had different initial moisture content, I made comparison easier by using relative moisture content (Y) instead of the absolute one (w) at different power levels as the function of the operating period (Figure 2). I represented the standard deviation values derived from the 5 measurement series. Analysing the standard deviation values, it can be stated that the biggest deviation between measurement series appears in the middle period of the drying processes, but the magnitude of the deviation decreases as the level of power grows. The graphs gained from the experiments are similar to those of the classical

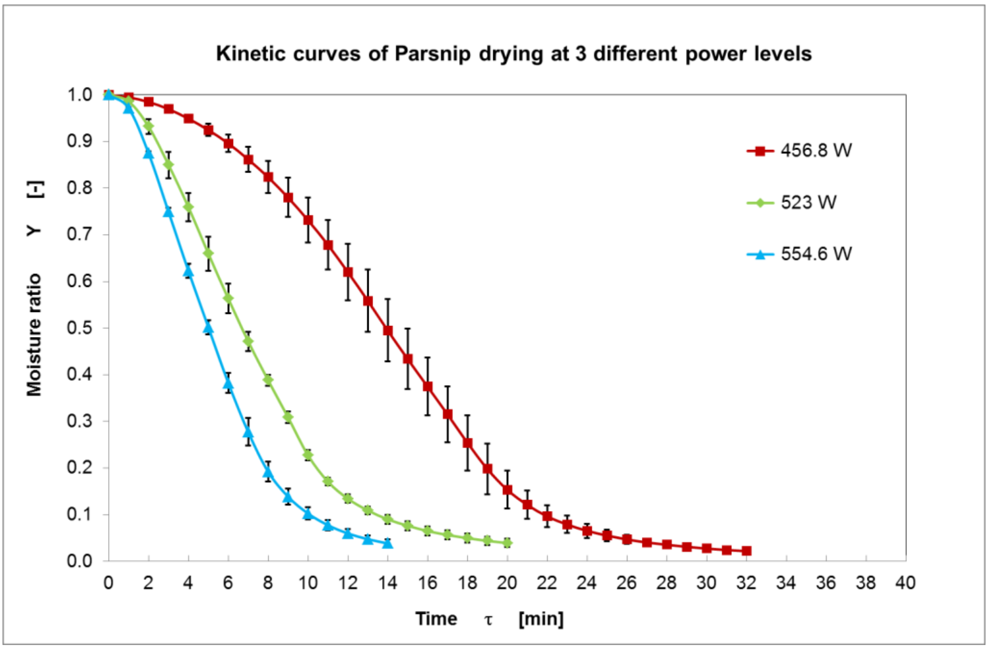

Figure 2. Kinetic curves of Parsnip drying at 3 different power levels

convective drying processes. The deviation appears in the time period of the process, which is much shorter because of the form of energy transfer (thus the graph is steeper) than in the convective case. The different phenomena can be explained by the effect mechanism of microwave energy. As energy absorption is proportional to the moisture content of the samples, furthermore, the thermic effect appears where the treated material contains water, the initial heat-up phase and the final asymptotic phase with reducing drying speed become shorter. Drying kinetic graphs illustrate that increasing the applied power level, the operating period reduces.

Wet base moisture content (w) makes possible to calculate the value of dry base moisture content (X). Drying rate (S) can be charted as a function of dry base moisture content, which shows the change of moisture content in a given time unit. See Figure 3 for the drying rate graphs at power level 3. This Figure unambiguously shows that increasing the power makes drying rate values grow higher. During determining the functional connection between the examined properties, I aimed to find as simple formula as possible which still describes the process with sufficient accuracy. In the case of each plant I tried to find a formula using all the points gained during the whole drying process, applying the method of the least squares. As a result, I was able to approximate the points with the graph of a third grade polynomial with sufficient accuracy (the minimal value of the coefficient of determination was $R^2 = 0.9$).

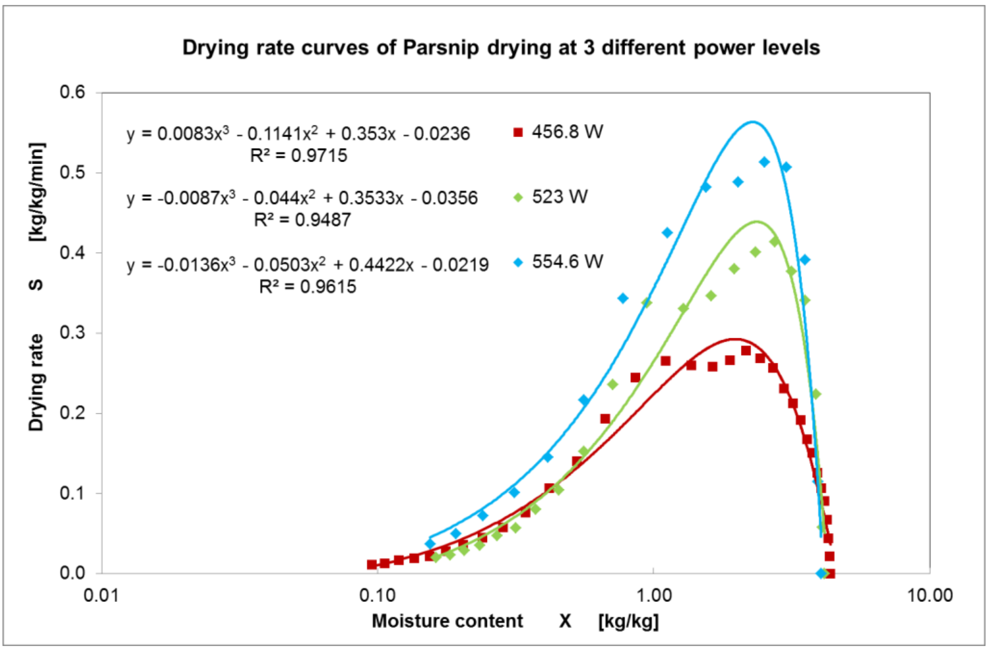

Figure 3. Drying rate curves of Parsnip drying at 3 different power levels

As the section with permanent drying rate, which characterizes the convective drying processes of classical agricultural materials was not detectable under the applied experimental circumstances, thus the relevant properties from the point of view of the drying process were worth analysing at the segment of the decreasing drying rate. To make this analysis possible, I determined the maximum value of the calculated drying rate values in the case of each measurement. Henceforth, I only determined the calculated properties of this section.

As the next step, using the dissipated performance data, I calculated the specific drying rate values. The specific drying rate shows the drying rate values belonging to the energy consumption of losing a mass unit of water by dehydration. Thus, the drying rate values of different series of measurements can easily be compared. See Figure 4 for the specific drying rate values belonging to the decreasing drying rate section of parsnip measurements as function of the dry base moisture content. The specific drying rate values show that applying higher operating power levels increases the value of drying rate. In Figure 4, I indicated the equations which describe each level of power as well as the coefficients of determination which belong to them. As you can see, the points of this Figure can be approximated with sufficient accuracy by a quadratic polynomial. (The value of the coefficient of determination R^2 was greater than 0.84 in the case of each examination.)

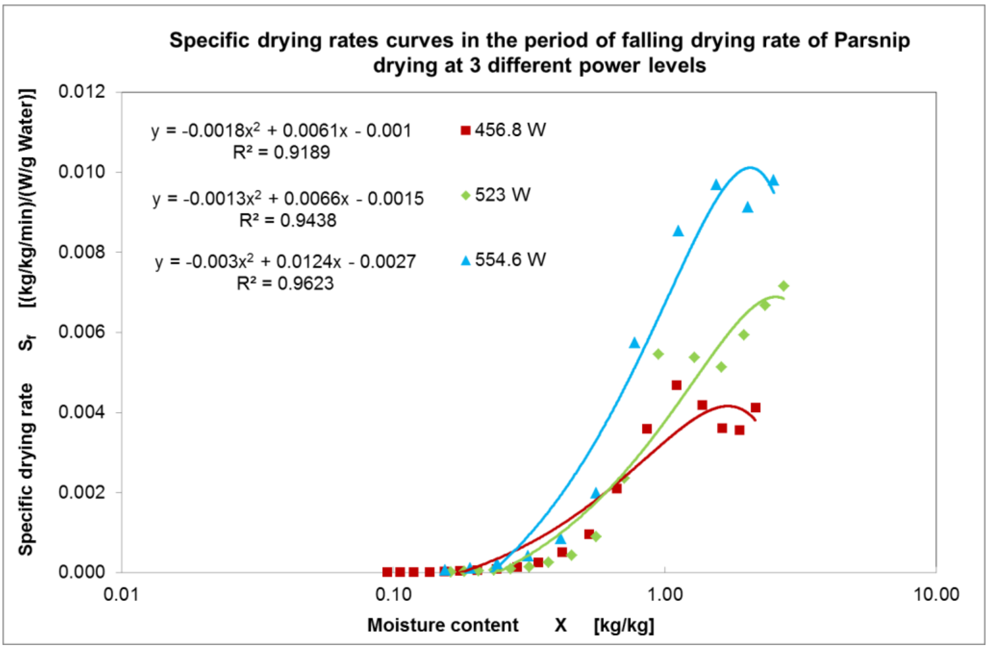

Figure 4. Specific drying rates curves in the period of falling drying rate of Parsnip drying at 3 different power levels

The general form of the describing equation is:

$$S_f = a \cdot X^2 + b \cdot X + c. \qquad (3.1)$$

Finally, as the last step of data processing, I determined the energetic indicators of the drying process. First, I calculated the energy consumption of the whole process, subdividing it into sampling sections. From these values, related to the section of the decreasing drying rate, I chose the minimal value as base of comparison. The other values of the process are given as relative energy requirement based on the selected value, then I charted them as a function of the dry base calculated moisture content. In Figure 5 I charted the relative energy requirement of the parsnip. Relative energy requirement graphs can be divided into two well separable parts in the case of each plant and each power level. In the section of the decreasing drying rate, the energy requirement can be considered constant, then the graphs start to elevate steeply. The lengths of the constant section differ, depending on the plant type and the level of power.
I charted the above mentioned diagrams for each plant, and used them to examine the behaviour of the certain plant groups.

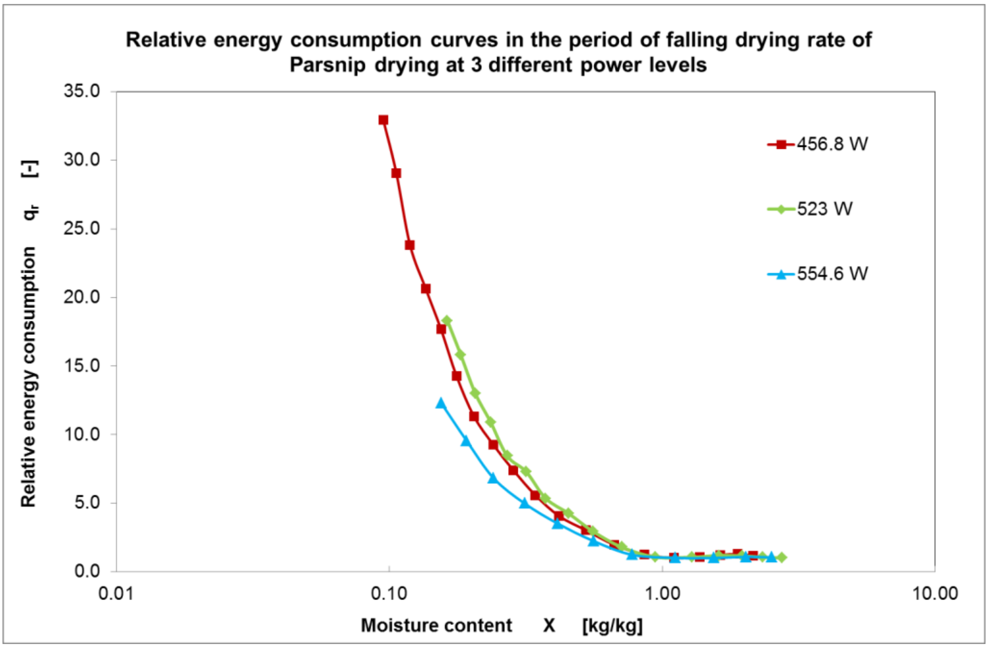

Figure 5. Relative energy consumption curves in the period of falling drying rate of Parsnip drying at 3 different power levels

3.2. Examination of root vegetables

After processing the data of each plant, I examined the common properties of plant groups. First, I compared the drying graphs. As expected, growing microwave powers entail shorter operating periods. The experienced

30-minute-long operating period at the 456.8 W level decreased to 20 minutes at the 523 W level and to 14 minutes at the 554.6 W level.

For the group of root vegetables, I charted the drying rate graph of the whole process, then I charted the specific drying rate values as a function of the dry base calculated moisture content. I also approximated the graphs with a quadratic polynomial (Equation 3.1). I drew the graphs of all 4 plants, which can also be approximated by a quadratic equation, and at each power level, the value of the coefficient of determination exceeds 0.85, which indicates an exact incidence given the properties of the dried material. It can undoubtedly be established that the properties of the 4 plants can be characterized well one-by-one with the formula of the whole group. Drawing the individual power graphs in one diagram (Figure 6), the proportional connection is apparent, namely, increasing the power, entails an elevated value of the drying rate. At the 554.6 W power level, specific drying rate is almost three times as much as the value belonging to the 456.8 W power level.

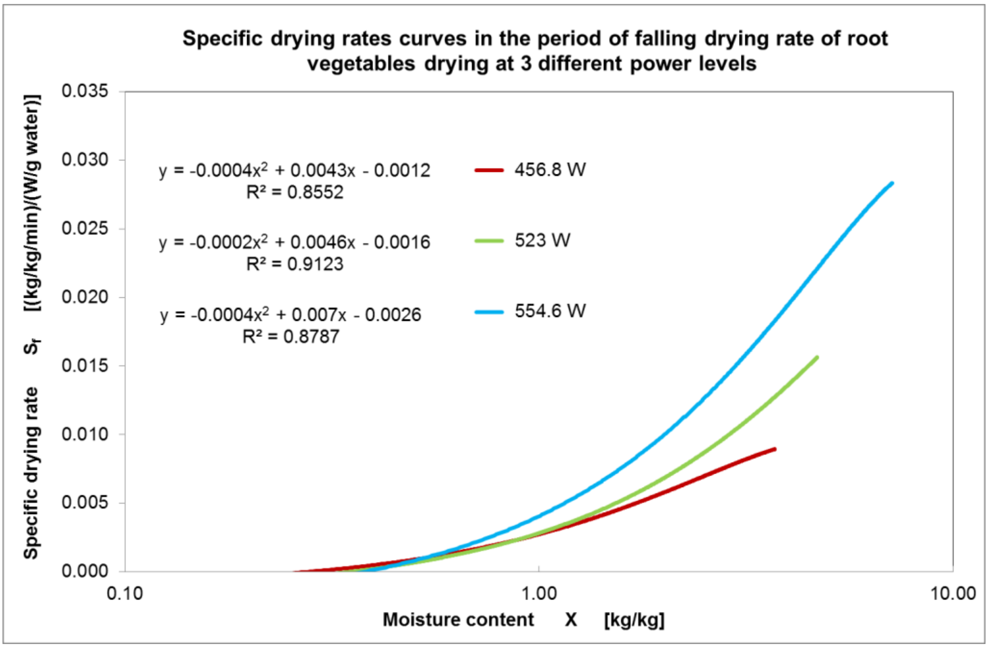

Figure 6. Specific drying rates curves in the period of falling drying rate of root vegetables drying at 3 different power levels

Similarly to the methods used in the case of individual plants, the last step was examining the relative energy requirement. First, I plotted the graphs belonging to the different power levels individually, one-by-one. The graphs of the relative energy requirements in the case of each plant were characterized by their being divided into two different sections. Similarly to the phenomenon experienced in the case of the parsnip, in the domain of the higher moisture content, the energy requirement can be considered constant, then after a critical point, the energy requirement starts to grow steeply. In the case of plants with higher initial moisture content, the starting point of the growing section is shifted to the direction of the higher moisture content. The determination of the critical point which separates the two phases is of utmost importance, because this is the only way of totally describing the section with growing energy requirement. On the basis of the diagrams, it can be established that the formation of the unambiguously increasing phase especially depends on the applied power. At the 456.8 W level, thanks to the low power level applied, the transition is gradual, which makes the exact determination of the critical point difficult. On the contrary, at the 554.6 W power level, there is a sharp change, which unambiguously shows the location of the critical point.

After determining the location of the critical point, I drew the diagrams of the increasing phase, and I tried to find a functional connection between the moisture content and the relative energy requirement. The changes of the increasing phase can be approximated accurately by a simple power function, whose general formula is:

$$q_r = a \cdot X^b \, . \qquad (3.2)$$

I also indicated the equations related to the individual plants. You can see in the diagrams that at all power levels, in the case of the parsnip with low initial moisture content, the formation of the segment of the increasing relative energy requirement corresponds with the values with low moisture content. However, in the cases of the carrot and the celery, whose initial moisture contents are higher, this point is shifted to the direction of the phase with a higher moisture content, which undoubtedly indicates the dependence of the situation of the critical point on the moisture content. By elevating the power level, the difference between the moisture contents of the starting points is increasing because of the elevation of the amount of energy per material unit.

As the critical points can be associated to different moisture contents in the cases of each plant, I shifted the graphs of the increasing phase to a common starting point, to make comparison easier. For this, I calculated the relative dry base moisture content, for which I used the moisture content of the critical point as base, and I expressed all the other values on this basis. The graphs of the relative energy consumption which belong to the individual power levels were drawn on the increasing segment as the function of the relative moisture content. I also determined this functional connection on each level, then I drew the graph which fits all the measurement points of the 4 functions, which can be approximated using 3.2 power function as follows.

$$q_r = a \cdot X_r^b . \qquad (3.3)$$

Analysing the cumulative results belonging to the different power levels, you can see that increasing the level of power, the fitting accuracy of the function decreases in a small compass. This phenomenon indicates that increasing the power entails a stronger expression of the difference between the individual dehydration properties. See Figure 7, in which I drew all the cumulative graphs at power level 3, where you can see that the gradation of the graphs decreases, which refers to the fact that the initial point of the increasing phase of the relative energy requirement is shifted to the direction of the higher moisture content. Moreover, by increasing the power, the maximum values of relative energy requirement significantly decrease. In the case of the root vegetables, it means that drying at the 456.8 W power level has more than twice as much energy requirement than at the 554.6 W power level.

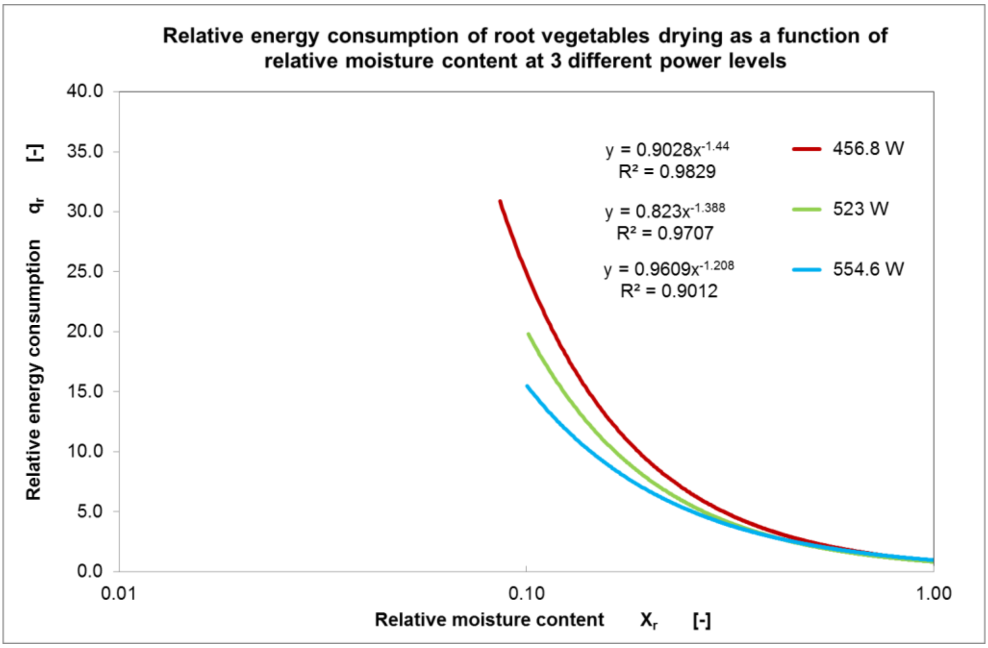

Figure 7. Relative energy consumption of root vegetables drying as a function of relative moisture content at 3 different power levels

3.3. Examination of Solenaceae

The processing method of the data of examining Solenaceae group showed a high value of correspondence with the method exposed at the root vegetables. As the initial moisture content of the examined plants were also different in this case, first, I drew the moisture relation graphs of this plant group. The classical drying curve shape can be observed during the drying of Solenaceae, but in this plant group, there are more significant morphological differences than in the group of root vegetables, so the graphs also show bigger differences, especially at the final phase of the drying process. This discrepancy decreases when a higher level of power is applied, but there is some difference even at the highest level. Similarly with the experience on root vegetables, discrepancies in initial moisture content influence the desiccating process. Thus, the drying graphs of the potato turned out to be steeper than those of the 3 other plants which have much higher initial moisture content. One of the main reasons of the difference in moisture content is that during the experiments, I dried the thickened stem of the potato while in the case of the other plants, their crops. Moreover, there is a minor difference in the structure of the crops, hence while the eggplant has a mostly homogeneous, solid flesh, the crop flesh of paprika is much thinner with a skin-like structure.

Comparing the curves of the 3 power levels, it also holds for potato that increasing the microwave performance makes operating periods shorter. Practically, it means that the time of drying varies - depending on the plant - between 26 and 32 minutes at the 456.8 W level, between 20 and 22 minutes at the 523 W power level, and between 12 and 14 minutes at the 554.6 W power level.

I went on analysing the Solenaceae group by drawing the graphs of the drying velocities by individual plants, then that of the specific drying velocities, which showed a significant resemblance in tendency to what I experienced in the group of root vegetables. I also approximated the graphs with a quadratic polynomial (Equation 3.1), which only differed from those of the root vegetables in the coefficients. The describing functions approximate them well because the value of the correlation coefficient exceeds 0.84 in each case. The fitting of the cumulative graphs slightly decreased mostly because of the previously mentioned morphological properties, but the $R^2 = 0.74$ value at the 456.8 W power level can be considered sufficient during drying agricultural products. Moreover, if you compare the graphs of the different power levels in detail (Figure 8), you can see that increasing the power level results in growing accuracy in the approximation, which means that the drying properties of the individual plants become more and more similar. Paying attention to the maximum value of the drying rate values, similarly to the root vegetables, it can be observed in the Solenaceae group that increasing the microwave performance entails the increasing of the specific drying rate. On the other hand, there is a significant difference in the rate of growth. While the growth of the specific drying rate of the root vegetables is three-fold, in the case of the Solenaceae group it is approaching the five-fold value.

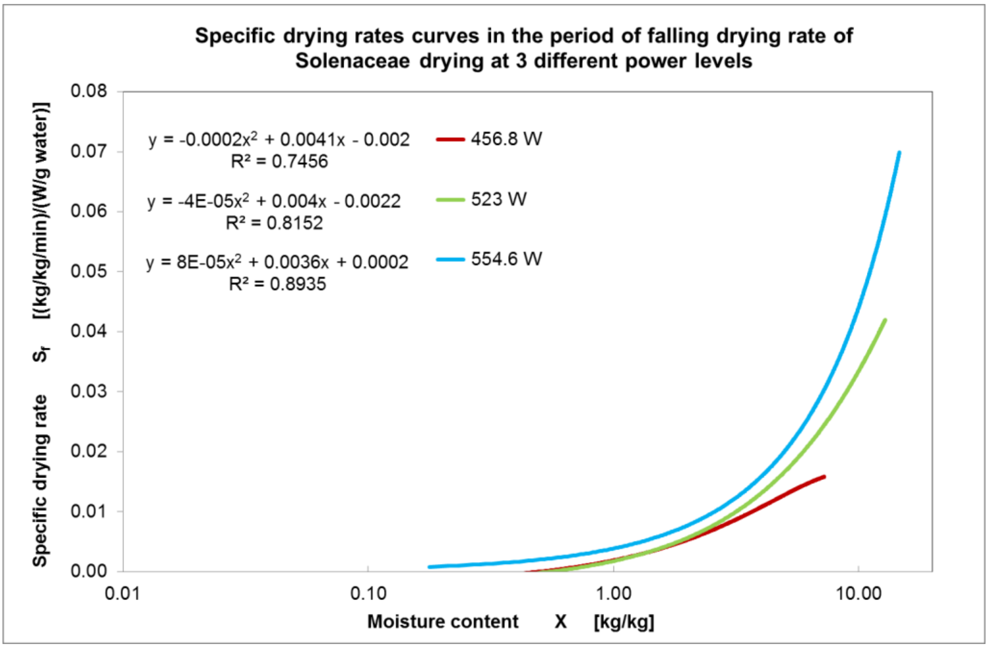

Figure 8. Specific drying rates curves in the period of falling drying rate of Solenaceae drying at 3 different power levels

In order to introduce the energetic relations of drying processes, I determined the specific values of energy requirement in the Solenaceae group, then using them in the same way as I had discussed it before, I calculated the relative energy requirement values, which I charted as the function of the dry base moisture content. The two parts of the graph of relative energy requirement that showed different properties, were separable in this case, too. In the range of high moisture contents, the relative energy requirement can be considered constant, while at low moister content, there is an intensive growth. This process, which can be separated into two phases, gives totally the same results as those of the root vegetables. The similarity of energy consumption is supported by the fact that by increasing the microwave performance, there is a definite transition between the two phases.

For analysing the increasing phase, similarly as before, I calculated the moisture content value, which belongs to the point that separates the two phases, for each individual plant. Comparing the critical points of each plant, it can be established that the critical point of the Solenaceae group does not coincide to such extent, as that of the root vegetables. The reason of this phenomenon is the higher difference between the initial moisture contents on one hand, and the morphological differences of the plants on the other hand. Similarly, as it was experienced in the case of root vegetables, it holds for the plants of the Solenaceae group, that the relative energy requirement graphs of plants with a lower initial moisture content change to the intense increasing phase in the range of lower moisture contents. After determining the location of the critical point, I drew the diagrams of only the increasing phase, and I tried to find a functional connection describing the growth of energy requirement. In each case, the most accurate approximation was the power function which I used at the root vegetables (3.2).

In the last part of the examination, I compared the relative energy requirements which belong to each performance level. On account of the different moisture contents of the critical points, I constituted a starting point, as I had done in the case of root vegetables, as base of comparison for expressing the relative moisture content values. Then I charted all the relative energy requirement points of the 4 plants as function of the relative moisture content. The most accurate approximation of the curve which fitted all the points was the power function which I used at the root vegetables (3.3). The accuracy of fitting is a bit lower than that of the root vegetables, which has several reasons. On one hand, it can be observed on each power level, that the relative energy requirement values of the paprika show a slightly different, steeper tendency, compared to the other 3 plants. It is bound to the difference of the dried samples. The paprika samples could not be cut into perfect cubes because of its thin crop flesh, thus its sample units had to lose less water. As a result, the way of its desiccation is different from that of the other plants. On the other hand, the morphological properties that influence the desiccation of the crops, do not show such resemblance as in the case of root vegetables.

See Figure 9, where I charted the cumulative graphs of the different power levels. The graphs of Figure 9 illustrate the same correlation between energy requirement and relative dry base moisture content as in the case of root vegetables, namely, by increasing the power, the steepness of the graphs of relative energy requirement decreases. Therefore, it also holds for the Solenaceae group that applying higher microwave performance shifts the location of the critical point in the direction of higher moisture content.

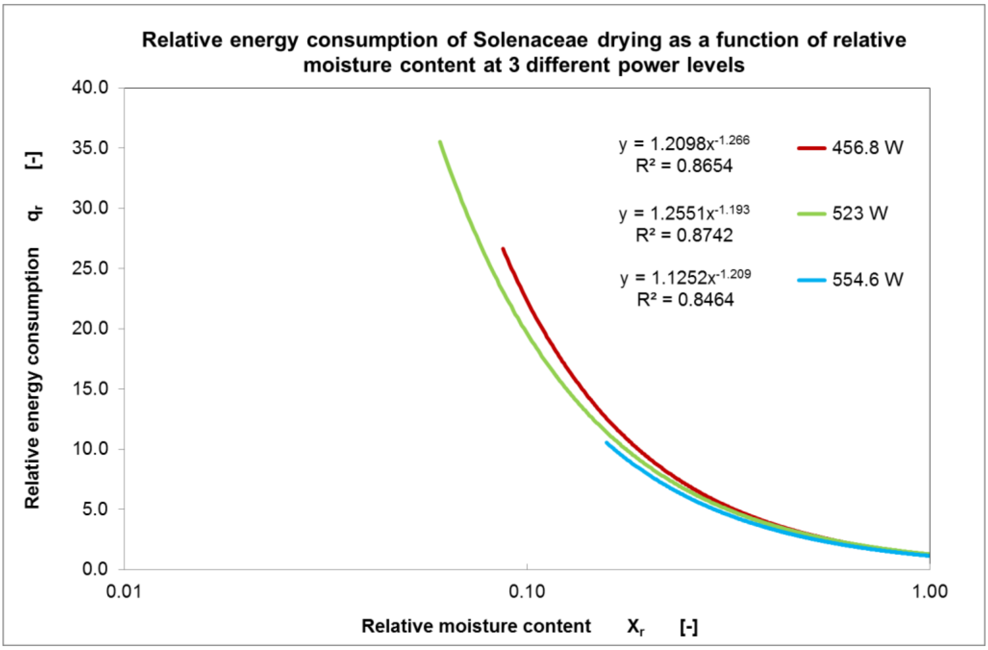

Figure 9. Relative energy consumption of Solenaceae drying as a function of relative moisture content at 3 different power levels

3.4. Examination of leaf vegetables

In this chapter, I describe the examination of check samples, for which I chose drying the leaves of the leaf vegetables of Umbelliferae group, as this part of the plant significantly differs in its morphological structure from the previous two groups.

Though the drying method of leaf vegetables is partly different from the measurements of the other two groups, the results obtained support the previous connections. The filling of the microwave sample space is the double than that of the Solenaceae group or the root vegetables, but the mass of the sample was only 25 g, while the other samples weighed 80 g.

I chose the middle power level, the 523 W level for the check samples, in order to eliminate the disadvantages caused by the too high or too low power. At this power level, I examined 3 kinds of leaf vegetables, whose results were analysed by me as described in 3.1, then I charted the results.

I charted the drying kinetic graphs first, but there were significant differences in initial moisture content in this plant group, therefore I also charted the moisture relation values as the function of the operating period. The shape of the curves are as expected during microwave energy conveyance, as soon after starting the operation, the moisture content steeply decreases. The graphs of the plants of the group progress together during the operating period, namely, the water egresses of the plants of the group are similar to each other. In spite of the high initial moisture content, due to the low mass of the samples, the operating period was only 11 minutes for each plant. Specific drying rate graphs also confirm the conclusion about the similarity of water egression (See Figure 10). This Figure unambiguously shows that the values of the specific drying velocities of the plants show a uniform pattern. The cumulative quadratic function which belongs to the whole group - as in the case of the root vegetables and the Solenaceae group - fits all the measured points with high accuracy.

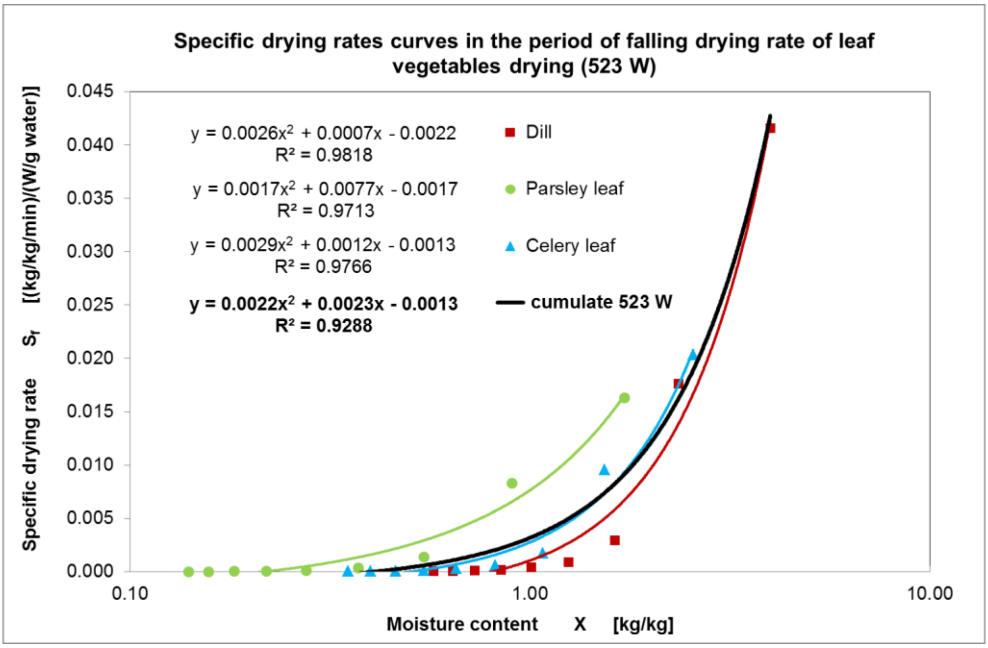

Figure 10. Specific drying rates curves in the period of falling drying rate of leaf vegetables drying (523 W)

Charting the relative energy requirement graphs of the different plants as function of the dry base measured moisture content, we obtain the well-known shape from the diagrams of root vegetables and the Solenaceae group, whose two segments can easily be observed. In the case of the leaf vegetables, at high moisture content, the relative energy requirement can be considered constant, while at low moisture content phase, there is an intense growth. The constant phase is shorter in the case of the leaf vegetables, as the mass of the sample was lower than during the measurements of the other two plant groups, thus the values of the specific energy requirement are also higher. Similarly to the two previous groups, the critical point appears at a lower moisture content, if the initial moisture content is low, while at a higher moister content, if the initial moisture content is high.

Considering all the above statements, the increasing phases of all 3 plants can be characterized by the equation given in (3.2). For comparing the 3 plants, I also used the dry base measured moisture content. Charting the relevant points in a diagram (Figure 11), there exists a relative energy requirement function which characterizes the whole group, and whose formula is the same as that of the two previous groups (Equation 3.3).

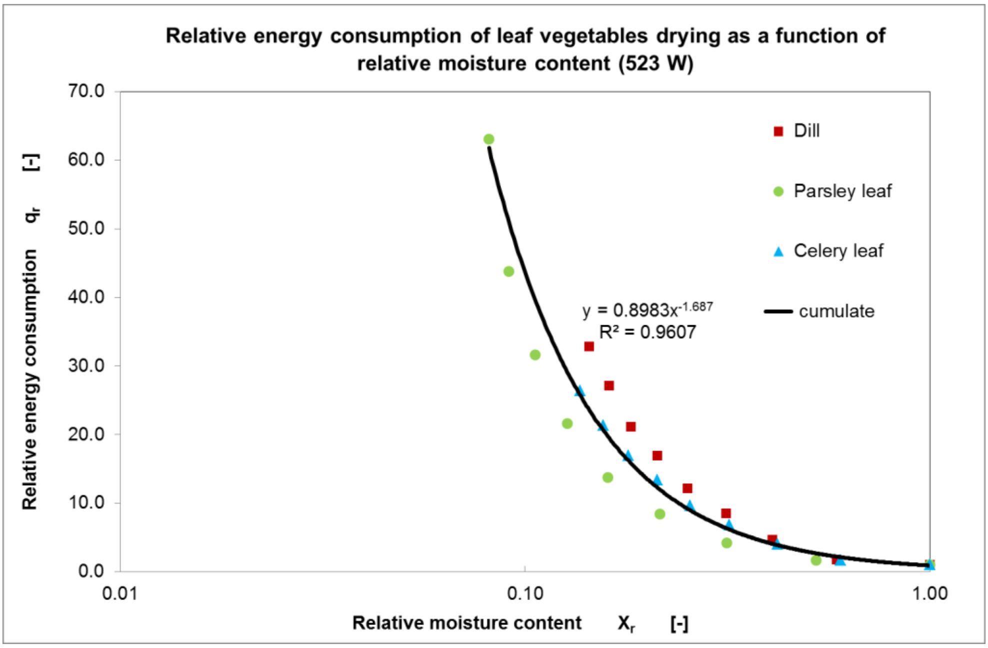

Figure 11. Relative energy consumption of leaf vegetables drying as a function of relative moisture content (523 W)

To sum up the experience of the measurements of the leaf vegetables, I can draw the conclusion that though the morphological structure of this plant group is different from those of the two previous groups, still the results can be expressed by the same formulas. The only difference appears in the coefficients, which depend on the plant group.

4. NEW SCIENTIFIC RESULTS

1. Relying on experiments, I determined the functional connection between the specific drying rate and the dry base measured moisture content in the phase of decreasing drying rate. The function can be expressed by a quadratic polynomial whose general formula is:

$$S_f = a \cdot X^2 + b \cdot X + c.$$

The coefficients of some plant groups are enumerated in the following chart:

Magnetron Power	Plant group	Coefficients of the equation			R^2
		a	b	c	
456.8 W	Root vegetables	-0.0004	0.0043	-0.0012	0.8552
	Solenaceae	-0.0002	0.0041	-0.002	0.7456
523 W	Root vegetables	-0.0002	0.0046	-0.0016	0.9123
	Solenaceae	-0.00004	0.004	-0.0022	0.8152
	Leaf vegetables	0.0022	0.0023	-0.0013	0.9288
554.6 W	Root vegetables	-0.0004	0.007	-0.0026	0.8787
	Solenaceae	0.00008	0.0036	0.0002	0.8935

The coefficients of the equation that describes the process are the same values in a given morphological group and this statement holds for each examined plant group. I determined this formula for the root vegetables of the Umbelliferae group and for the Solenaceae group. In order to check my results, I determined the formula for the leaf vegetables of the Umbelliferae group, and it supported my calculations. The difference between the individual groups can be described by calculating the coefficients.

2. I proved by experiments that during microwave drying, the phase of decreasing drying rate can be divided into two well divisible phases from the point of view of energy consumption. The first phase can be characterized by higher moisture content and constant relative energy requirement. The second phase, which can be characterized by low moisture content, can be described by a progressive function. This division caused by energy requirement can be detected at all the three plant groups, whose morphological structures are significantly different.

3. I proved by experiments that the location of the critical point that separates the two energetic phases is determined by both the applied microwave power level and the morphological structure of the plant group together. Within a certain morphological group, applying higher microwave power shifts the location of the critical point in the direction of higher moisture content.

4. I determined a functional connection between relative energy requirement and the relative dry base measured moisture content on the phase which follows the critical point, whose general formula is:

$$q_r = a \cdot X_r^b.$$

I calculated the coefficients of the equation of the elaborated function for all examined plants and plant groups. As the morphological structures of the plants determine the magnitude of the energy requirement, calculating the coefficients of the equation, the energy consumption of groups with different morphological structures can be calculated. The coefficients of the different plant groups are enumerated in the following chart:

Magnetron Power	Plant group	Coefficients of the equation		R^2
		a	b	
456.8 W	Root vegetables	0.9028	-1.44	0.9829
	Solenaceae	1.2098	-1.266	0.8654
523 W	Root vegetables	0.823	-1.388	0.9707
	Solenaceae	1.2551	-1.193	0.8742
	Leaf vegetables	0.8983	-1.687	0.9607
554.6 W	Root vegetables	0.9609	-1.208	0.9012
	Solenaceae	1.1252	-1.209	0.8464

5. By measuring the leaf vegetables, I proved that the statements related to the shape and character of the drying curves and to the two phases of relative energy requirement - including the formula of the equation describing the increasing phase - do not depend on the filling of the microwave space. Though, during the experiments, the filling index of the leaf vegetables were significantly different from that of the Solenaceae group and the root vegetables, the statements concluded for the two other morphological groups hold for the leaf vegetables, too.

5. CONCLUSIONS AND SUGGESTIONS

In the framework of my research, I examined the drying properties of certain plant groups during microwave energy conveyance. During the drying experiments, numerous additional questions arose which require further research.

During my research, I experimented on 3 plant groups, but I suggest the detailed examining of other plant groups with high initial moisture content. It would contribute to the extension of the results of present day research and it would make possible the calculation of coefficients for the equations describing the processes which characterize certain plant groups, therefore, they would facilitate the industrial utilization of the results.

Besides the new scientific results, I determined the formulas describing the increasing phase of the relative energy requirement, whose description made determining the critical moisture content, which indicates the transition, necessary. The location of the critical point can be given with the accuracy that arises from the 1 minute sampling period. With the more detailed examination of the segment surrounding the critical point, the process can be described with superior accuracy.

The device, which I specifically built for experimental purposes, made possible the detecting of more parameters than experimenting with a common household microwave oven would do. On the other hand, during my experiments, the extension of the operating space made possible only a slight difference in the amount of the material to be dried. This fact determined the magnitude of the microwave power. The reconstruction of the operating space may increase the dimensions and would solve this question.

In the case of each plant group, following the microwave drying process, I suggest a detailed quality- and inner content examination. As this point of view was not relevant during my experiment, they were not determined, but their knowledge is the basic condition of the industrial applications of the results. Getting to know the boundaries of the application of microwave drying makes possible to establish a combined drying method which gives the best results from each point of view.

The data derived from the experiments can be used to establish a uniform database about the agricultural products, which serves for the previous calculation of the water conveying processes of the materials among different initial conditions. It would also serve for determining criteria for the quality of materials, and to find connections between them.

Furthermore, this database can serve for describing energy- and material transport processes, and for calculating their properties during microwave drying. It could result in gaining a mathematical model which describes the process and helps determine unambiguously the role of the parameters that influence the drying processes of plants.

6. SUMMARY

In my dissertation I investigated such plant groups from agricultural products, which have high initial moisture content, but their morphological structures are noticeably different. My aim was to determine the relationships between the microwave energy transfer and the products to be dried that not only describe the properties of the plants, but also characterize the groups of plants with sufficient accuracy.

To fulfill these objectives, I carried out literature research, based on which I determined the main properties of the drying processes, discussing the problems in the microwave drying processes and the characteristics of energy transfer separately.

I compiled a series of experiments, in which the unique properties of 11 plants in total were studied, using three power-level settings were used. I evaluated the results obtained from experiments with individual plants and plant groups.

The results were presented using different charts, and based on those, I draw conclusions which are valid to the individual plants and plant groups.

By evaluating the results of the experiments, I obtained the following new scientific results about microwave drying processes of agricultural products:

In the falling drying rate period, I determined the relationship between the specific drying rate of individual plants and plant groups and their moisture content. The formula for the relationship was same in each case, they only differed in the values of coefficients.

I proved that in the period of falling drying rate, the relative energy consumption, which depends on the moisture content, could be divided into a constant and an intensively increasing period, which can be well separated from each other.

Based on the results, I demonstrated that the position of critical point separating the two-phases is influenced by both the level of applied power and the morphological structure of the plant.

I determined the correlation describing the increasing phase of the relative energy consumption and its necessary coefficients for each plants and plant groups.

Finally, I proved by control measurements on leaf vegetables that the results do not depend on the fullness of the sample space of the microwave field.

I expounded my observations and comments that raised during the research process. These comments suggest a possible direction for further research and for the practical applications of the results.

7. MOST IMPORTANT PUBLICATIONS RELATED TO THE THESIS

Referred articles in foreign language:

1. Beke J., Bihercz G., **Kurják Z**. (2007): Simulation of drying process of corn kernels during microwave and convective treatment. Asia Pacific Journal of Chemical Engineering, 2007. (2), pp. 75-82.

2. Beke J., **Kurják Z**. (2010): Development of vegetable drying process by combining convective and microwave methods. Mechanical Engineering Letters, Vol. 4. pp. 50-64. (HU ISSN 2060-3789)

3. Beke J., **Kurják Z.**, Bessenyei K. (2011): Analysing the microwave drying process of potato, apple and onion samples from energetic point of view. Mechanical Engineering Letters, Vol. 6. pp. 59-73. (HU ISSN 2060-3789)

4. **Kurják Z**., Barhács A., Beke J. (2012): Energetic analysis of drying biological materials with high moisture content by using microwave energy. Drying Technology, Vol. 30, (3), pp. 312-319. (ISSN 0737-3937 Print; 1532-2300 Online) (IF: 1.814)

5. Beke J., **Kurják Z.**, Bessenyei, K. (2014): Enhanced drying due to nonthermal effects from microwave irradiation. Drying Technology, Vol. 32, (11), pp. 1269-1276. (ISSN 0737-3937 Print, 1532-2300 Online) (IF: 1.518)

Referred articles in Hungarian language:

6. Bihercz G., **Kurják Z.** (2003): Sárgarépa- és paradicsomminták konvektív és mikrohullámú szárítási folyamatainak összehasonlítása. Mezőgazdasági technika, 2003. augusztus, 2-5. o.

7. Beke J., **Kurják Z.**, Bessenyei K. (2012): Konvekciós szárítási modellek alkalmazási lehetőségei a mikrohullámú szárítási folyamatokban. Mezőgazdasági technika, 2012. július, 30-32. o.

8. **Kurják Z.**; Bessenyei K. (2014): Morfológiai hatások a száradási folyamatban konvektív és mikrohullámú energiaközlés esetén. Mezőgazdasági technika, 2014. június, 2-5. o.