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Study of the Safety Characteristics of Different Types of Pepper Powder (*Capsicum* L.)

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Abstract: This research was aimed at comparing the fire characteristics of different types of pepper in the context of explosion prevention. The following characteristics were studied: explosion pressure P_{max} and K_{st} at selected concentrations, ignition temperature of the deposited dust layer from the hot surface, and minimum ignition energy. The comparison of the chemical properties of the used types of pepper was performed using TG/DSC. The results of the measurements suggest that different types of peppers exhibit different explosion characteristics. Each sample reached the maximum value of the explosion pressure and rate of pressure rise at different concentrations. The volume of the explosion chamber used also influenced the explosion characteristics. It is a consequence of the fact that the explosion characteristics strongly depend on the mechanism of action of a particular igniter. The minimum effect on the safety characteristics was observed when measuring the minimum ignition energy and the minimum ignition temperature of the dust layer from the hot surface. The results of the measurements suggest that different types of peppers exhibit different explosion characteristics. This information should then be considered in explosion prevention.

Keywords: dust explosion; pepper samples; explosion characteristics; explosion protection

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1. Introduction

The food and wood processing industries frequently use flammable natural powder substances, which can explode under certain conditions.

These flammable natural materials are not composed of a single chemical substance. They usually consist of several components (there can be dozens or hundreds...). Even if they are the same species (food and wood), their composition is not the same. They usually differ in the content of chemical components. Differences in composition can affect fire parameters. There are many varieties of peppers. They differ in the content of oil components, trace elements, sugars, proteins, or capsaicin. When processing and grinding dried pepper, an explosive cloud may occur. Depending on the variety of pepper, they can have different fire parameters. For the optimal application of explosion prevention principles, it is necessary to know the fire parameters of all varieties that are processed. This is the only way to ensure that the highest achieved parameters will be detected. Only then, explosion prevention measures protect technology, people, and the environment during the entire technological process.

In the article, we focused on measuring and evaluating the fire parameters of different varieties of powdered pepper and whether these pepper parameters have the same value.

In order to ensure work safety, it is necessary to apply the principles of explosion prevention in the food and wood industries.

When designing explosion prevention, it is necessary to know the properties of the materials being handled. Effective explosion protection measures rely on safety characteristics. These are experimentally determined values that help in the prevention of an explosive atmosphere like the minimum explosive concentration (MEC) or the limiting oxygen concentration (LOC), below which a flame cannot propagate. This is called primary explosion protection. If it is not possible to stay below these values, the determination of the minimum ignition energy (MIE) and the minimum ignition temperature (MIT) helps avoid ignition by avoiding ignition sources exceeding these values (so-called secondary explosion protection). If it is neither possible to avoid an explosive atmosphere nor to eliminate the possibility of ignition sources, explosion characteristics like the maximum explosion pressure (P_{max}) and the maximum rate of pressure rise $(dp/dt)_{max}$ are used to mitigate the consequences of an explosion (so-called ternary or constructive explosion protection).

Five commercially cultivated species of chili or peppers *(C. chinense*, *C. annuum*, *C. pubescens*, *C. baccatum*, and *C. frutescens)* and around 25 wild and semi-cultivated species are known. Peppers (*C. annuum* L.) can be classified as hot or sweet [1]. Bell peppers have different colours (red, green, orange, and yellow), depending on their ripening stages and capacity to synthesize chlorophylls or carotenoids. Bell peppers are an important source of vitamins (provitamins A, E, and C) and various bioactive compounds (phenolic compounds and carotenoids) [2].

Oloresin and other enriched extracs are pepper-derived products used in the industry. The most important pepper-derived product is the paprika powder with 70% of its production used as a spice. The total world supply of paprika powder is approximately 60,000 tons per annum in contrast to the 1400 tons of paprika oleoresin produced [3,4].

Bell peppers show high levels of water (dry up to 8% and fresh up to 90%) and carbohydrates (approx. 50%) with low protein (ca. 10%) and fat content (up to 5%). Additionally, bell peppers contain some compounds, such as vitamins (B, A, D, C, E, and K) and minerals (potassium, sodium, magnesium, calcium, and phosphorus) [2]. The authors of [5–7] investigated the average content of components in *Capsicum annuum* and *Capsicum chinese*.

Generally, the major amount of peppers is produced and consumed in powdered form as a spice (chilli pepper) or as a colorant (paprika) [3].

2. Materials and Methods

The following red-coloured dried pepper powder samples were used in this research:

- Type I—sweet bell pepper (*Capsicum annuum*);
- Type II—Hungarian wax pepper (*Capsium annuum*);
- Type III—Serrano chilli pepper—25,000 Scoville heat units (*Capsicum chinense*);
- Type IV—Cayenne chilli pepper—50,000 Scoville heat units (*Capsicum chinense*).

All pepper samples were dried in a laboratory oven at a temperature of 70 °C for 24 h. The pepper powder samples were additionally milled on a knife mill and sieved to obtain the same particle size. The average particle size (median) of the samples used for measurement was 71 µm (Table 1).

2.1. Explosion Characteristics

A 365L explosion chamber (KV-150M2 at Slovak University of Technology in Bratislava, OZM Research manufacturer, redesigned at Faculty of Materials Science and Technology in Trnava) and a 20L sphere (at the Faculty of Safety Engineering—VSB Technical University of Ostrava, Czech Republic, Kuehner AG manufacturer) were used to determine the explosion characteristics. The measurement was based on the EN 14034 Standard [8]. The conditions of the explosion characteristics measurement are listed in Table 2.

Table 1. Particle size distribution of samples.

Size (µm)	Type I	Type II	Type III	Type IV
>500	0.00	0.00	0.00	0.01
355–500	0.00	0.01	0.00	0.00
350–355	1.20	1.23	1.29	1.19
180–250	2.67	2.54	2.38	2.43
125–180	15.37	15.61	15.51	15.59
90–125	28.93	28.56	28.74	27.65
63–90	58.96	58.93	58.88	58.77
45–63	74.69	74.81	74.51	74.67
<45	100.00	100.00	100.00	100.00
Median	71.0	70.9	70.8	70.6

Table 2. Explosion characteristics measurement conditions in KV-150M2 and 20L sphere.

	KV-150M2	20L Sphere
Volume [L]	365	20
Sampling rate [Hz]	50,000	5000
Dispersing air overpressure [bar g]	10	20
Igniter	Sobbe	Sobbe
Igniter energy	2 × 5 kJ	2 × 5 kJ
Data evaluation	MATLAB Application	Kuehner Software KSEP 7.0
Temperature	Laboratory, 21 °C	Laboratory, 20 °C

The specific design solution of the KV150M2 chamber dispersing system is shown in Figures 1 and 2.

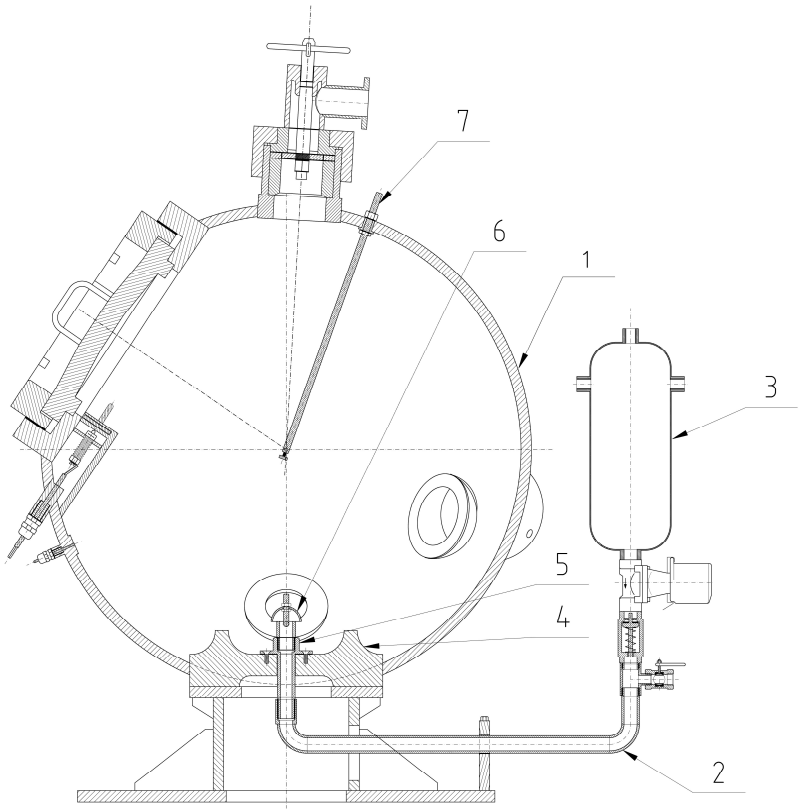


Figure 1. Cross-section of KV-150M2 explosion chamber (1—spherical explosion chamber with an internal diameter of 900 mm; 2—dispersing tube; 3—pressure vessel; 4—dispersing plate; 5 + 6—disperser; 7—igniter rod) [9].

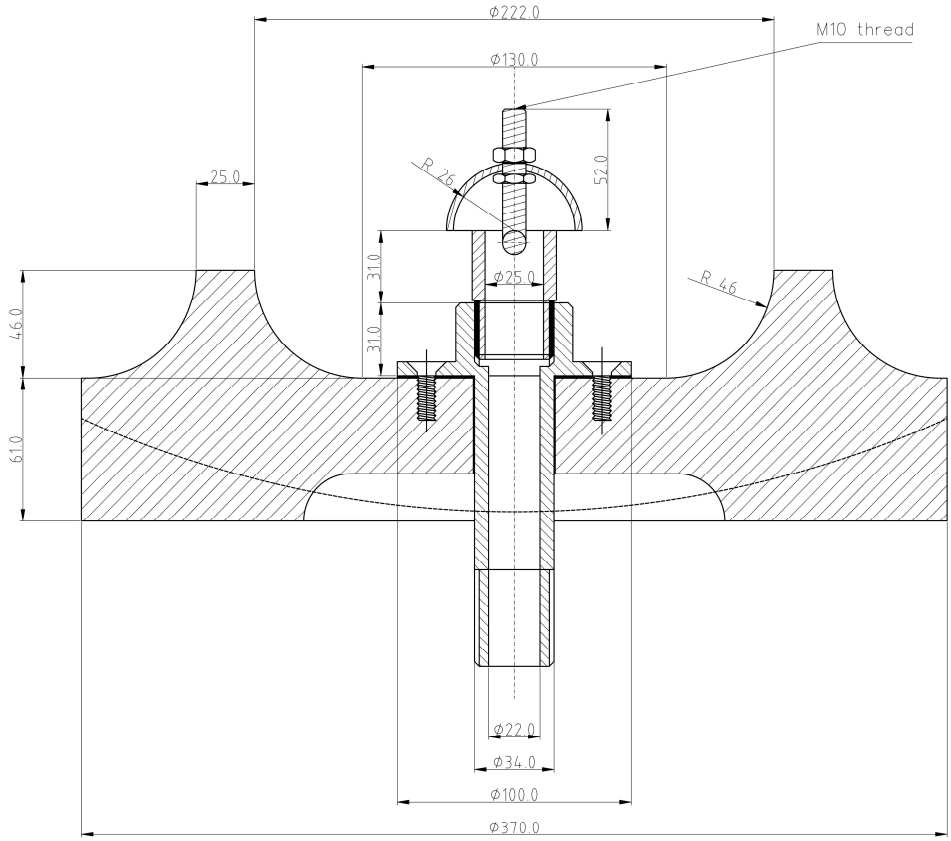


Figure 2. Cross-section of disperser [10].

2.2. Minimum Ignition Energy

The minimum ignition energy was measured using a standard MIKE 3 apparatus (manufacturer Cesana AG, Bettingen, Switzerland). The measurement was carried out in accordance with the requirements of the European EN 13821 Standard [11] and the American ASTM E 2019 [12] Standard. For all combinations (samples weighed: 150, 300, 600, 900, 1200, 1500, 1800, 2400, 3000, and 3600 mg; ignition delay times: 60, 90, 120, 150, and 180 ms), the dust was tested at least 10 times. When ignition occurred, the ignition energy was lowered, and all combinations were checked again. All tests were performed with an inductance of 1 mH in the circuit.

2.3. Minimum Ignition Temperature of Dust Layer

The ignition temperature of the dust layer from the hot surface was measured using the device (Classic CZ manufacturer) in accordance with the requirements of the EN ISO/IEC 80079 Standard [13]. The temperature of the dust layer (100 mm diameter, 5 mm height) was measured using two K-type thermocouples located in the dust layer. The temperature of the dust layer and the hot plate was recorded at a rate of 1 Hz.

3. Results and Discussion

The measurement in a 20L sphere was carried out at the Technical University of Ostrava, Faculty of Safety Engineering. The measurement was performed twice at each concentration.

The highest values of the pressure and the rate of pressure increase at individual concentrations are shown in Table 3. An example of the recording of a pressure curve in the 20L sphere is illustrated in Figure 3. The explosion constant was calculated with the following formula:

$$K_{ST} = \left(\frac{dP}{dt}\right)_{max} \times \sqrt[3]{V} \quad (1)$$

where $(dP/dt)_{max}$ is the maximum value of the sample's rate of pressure increase, and V is the volume of the chamber.

Table 3. Explosion characteristics of pepper samples in 20L (V = 0.02 m^3) sphere (Kuhner AG).

Concentration [g·m^{-3}]	Type I		Type II		Type III		Type IV	
	P_{max} [bar g]	dP/dt [bar·s^{-1}]	P_{max} [bar g]	dP/dt [bar·s^{-1}]	P_{max} [bar g]	dP/dt [bar·s^{-1}]	P_{max} [bar g]	dP/dt [bar·s^{-1}]
500	5.6	92	**6.9**	**136**	5.8	112	6.1	162
750	6.1	122	6.2	123	6.3	120	**6.3**	**168**
1000	6.2	126	6.2	114	**6.6**	**172**	5.9	127
1250	6.1	134	6.2	108	5.9	119	5.8	102
1500	**6.4**	**188**	5.9	108	5.9	113	5.8	106
1750	6	151	5.8	103	-	-	-	-
2000	5.9	121	-	-	-	-	-	-
K_{st} (bar·m·s^{-1})	51		37		47		46	

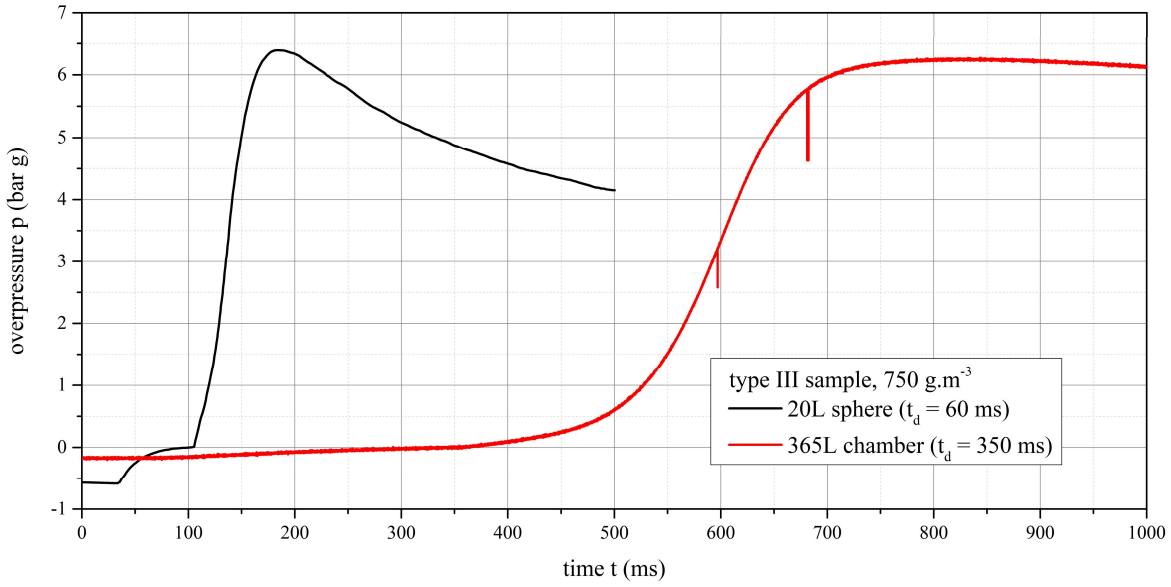


Figure 3. Comparison of pressure records in 20L sphere and in 365L chamber (Type III, 750 g·m^{-3}).

The maximum values of the explosion characteristics were measured for individual pepper samples at different concentration values. The results of the measurements indicate that the composition of different types of pepper influences explosion characteristics. The maximum value of the explosion pressure was achieved with Type II pepper (P_{max} = 6.9 bar @ 500 g·m^{-3}), and the highest value of the explosion constant was achieved with Type I pepper (K_{st} = 51 bar·m·s^{-1} @ 1500 g/m^{-3}). The explosion pressure reached a value of 6.3–6.9 bar (10% difference). The explosion constant was within the range of 37–51 bar·m·s^{-1} (difference of 27.5%).

The important fact is that each type of pepper reached its maximum explosion characteristics at different concentration values. This result is important in terms of explosion prevention. Though the same type of food product (pepper powder) is focused on, explosion characteristics significantly depend on the type of pepper used. In the food industry, it is therefore necessary to take into account also the varieties of food type dust when designing explosion prevention.

The measurement of explosion characteristics at the same concentrations was also carried out in the explosion chamber KV-150M2 at the Slovak University of Technology. The results (highest values) are listed in Table 4, and selected pressure records are shown in Figures 4–6. K_{st} has been calculated with Equation (1).

Table 4. Explosion characteristics of pepper samples in 365L (V = 0.365 m^3) sphere (KV-150M2).

Concentration [g·m^{-3}]	Type I		Type II		Type III		Type IV	
	P_{max} [bar g]	dP/dt [bar·s^{-1}]	P_{max} [bar g]	dP/dt [bar·s^{-1}]	P_{max} [bar g]	dP/dt [bar·s^{-1}]	P_{max} [bar g]	dP/dt bar·s^{-1}
500	0.3	-	0.38	-	3.15	9.0	3.15	9.2
750	3.96	8.7	**5.94**	**46.8**	**6.24**	**39.9**	4.63	13.8
1000	4.69	14.8	5.24	21.6	6.17	34.7	**6.38**	**49.3**
1250	6.15	**54.4**	4.93	16.7	5.47	26.3	5.74	37.2
1500	**6.24**	54.2	4.57	9.3	4.32	14.7	4.97	21.6
1750	5.91	33.9	-	-	-	-	-	-
2000	4.58	13.2	-	-	-	-	-	-
K_{st} (bar·m·s^{-1})	38.9		33.4		28.5		35.2	

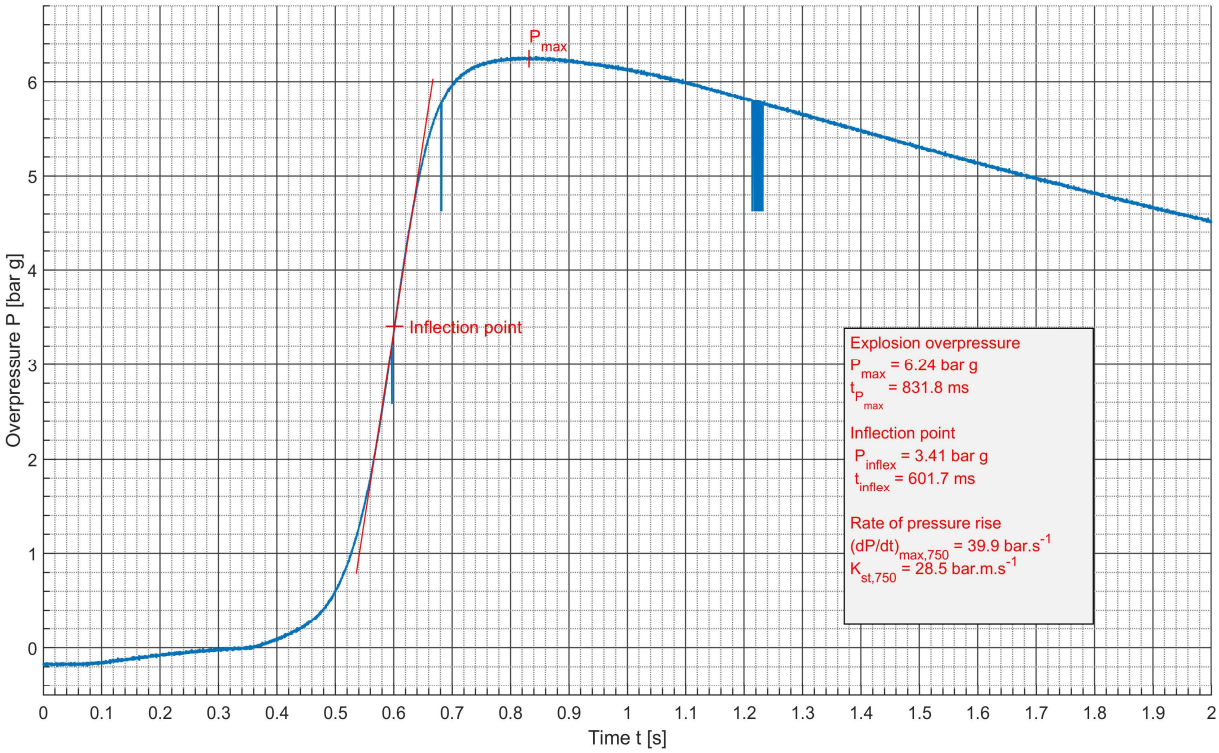


Figure 4. Pressure record of the Type III sample at 750 g·m^{-3}: a common pressure record curve shape.

The maximum value of the explosion pressure was achieved using the Type IV sample (P_{max} = 6.38 bar @ 1000 gm^{-3}), while the highest value of the explosion constant (K_{st} = 38.9 bar·m·s^{-1} @ 1250 g·m^{-3}) was achieved using Type I sample.

In the 365L sphere, the maximum explosion characteristics were achieved at different concentrations, similarly to those in the 20L sphere. The maximum explosion pressure was reached in the 365L chamber within the range of 5.94–6.38 bar (6.9%), while the explosion constant was within the range of 28.5–38.9 bar·m·s^{-1} (26.4%).

A comparison of the explosion characteristics of peppers in the 20L and 365L chambers indicates that the characteristics also significantly depend on the used test equipment. The explosion characteristics depend on the parameters of the dispersing system and the ignition mechanism. The cloud of ignition particles in the 365L chamber reaches about one-third of the chamber's volume. The cloud of ignition particles in the 20L chamber reaches the entire volume of the chamber. Therefore, the mechanism of cloud ignition and flame propagation in the chamber is different. The influence of the igniter and the mechanism of ignition of the dust cloud is also published in [14,15]. The explosion characteristics in devices of different volumes can also be influenced by the properties of the sample, such as

particle agglomeration or stickiness to the walls of the dispersing device since the sample contains oils.

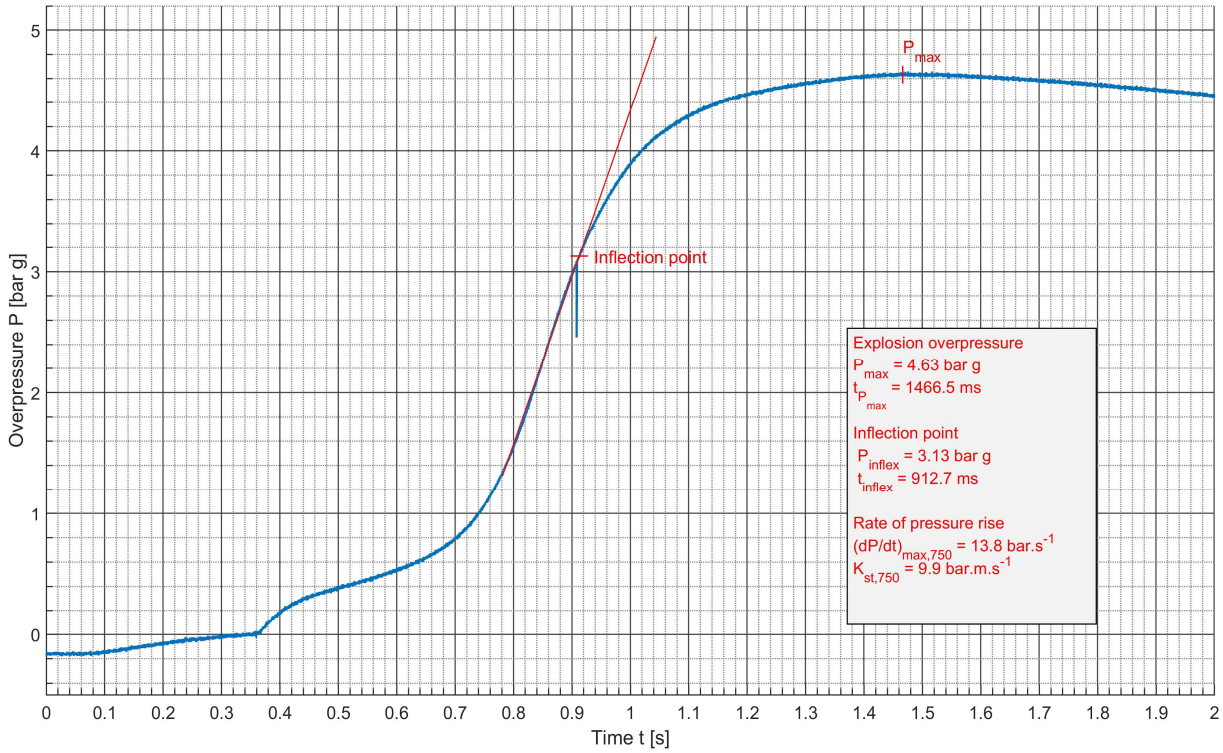


Figure 5. Pressure record of the Type IV sample at 750 g·m^{-3}: a pressure record curve shape with a slower sample to igniter reaction.

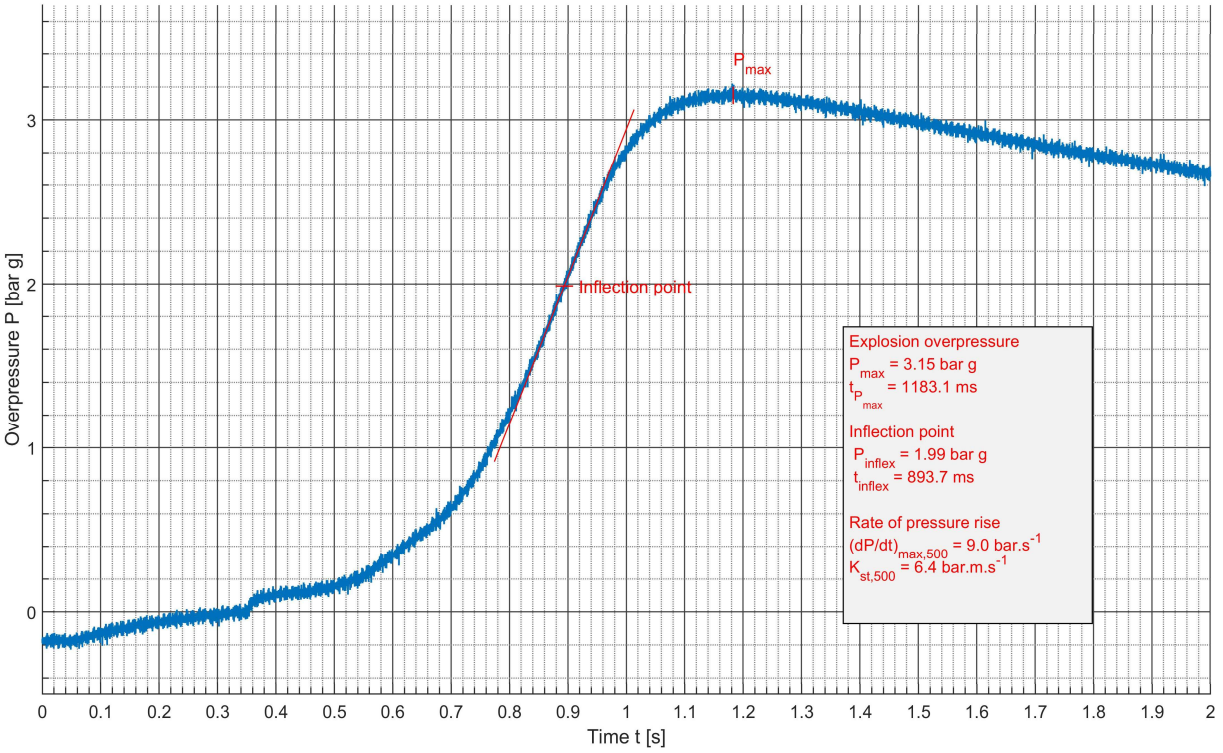


Figure 6. Pressure record of the Type III sample at 500 g·m^{-3}: a pressure record curve shape with a slower sample to igniter reaction.

In the 20L sphere, the sample is dispersed in the dispersion nozzle from the pressure vessel with the air. In this case, the friction and stickiness of the sample have an effect on the dispersion process.

In the 365L chamber, the sample is placed directly on the dispersion plate. The sample is dispersed by a stream of compressed air from a pressure vessel. The friction of the sample in the dispersing system is thus eliminated.

The mechanism of action of the ignition cloud also has a significant impact on the explosion characteristics. The value of the explosion pressure is similar in both devices (approx. 5.9–6.3 bar in the 365L sphere and 6.3–6.9 bar in the 20L sphere—a difference of up to 10%). The higher values of the explosion constant in the 20L sphere are due to the fact that, after the igniter in this sphere is activated, the hot particles of the cloud are dispersed throughout the entire volume of the 20L sphere [16,17]. Therefore, the sample particles are ignited in the entire volume of the 20L sphere. In the 20L sphere, a greater proportion of the sample particles is ignited by the ignition cloud simultaneously. The propagation of particle burning is thus faster, which also increases the rate of pressure increase during explosions.

In the 365L sphere, the hot particles of the igniter are dispersed in about 1/3–1/2 of the chamber's volume. The particles in this cloud are ignited, while the remaining particles are ignited by the propagation of the flame in the sphere [18].

The thermal analysis was performed on a METTLER TOLEDO TGA-DSC2 in an air atmosphere and a temperature range of 25 to 750 °C, with a temperature rise of 20 °C/min. The paprika powder samples at a weight of about 10 mg were placed in a corundum ceramic crucible.

TA for each type of pepper was performed only once. For better comparison, Figure 11 illustrates the thermal decomposition curves of all four types of peppers tested in separate figures.

The results are shown in Figures 7–11.

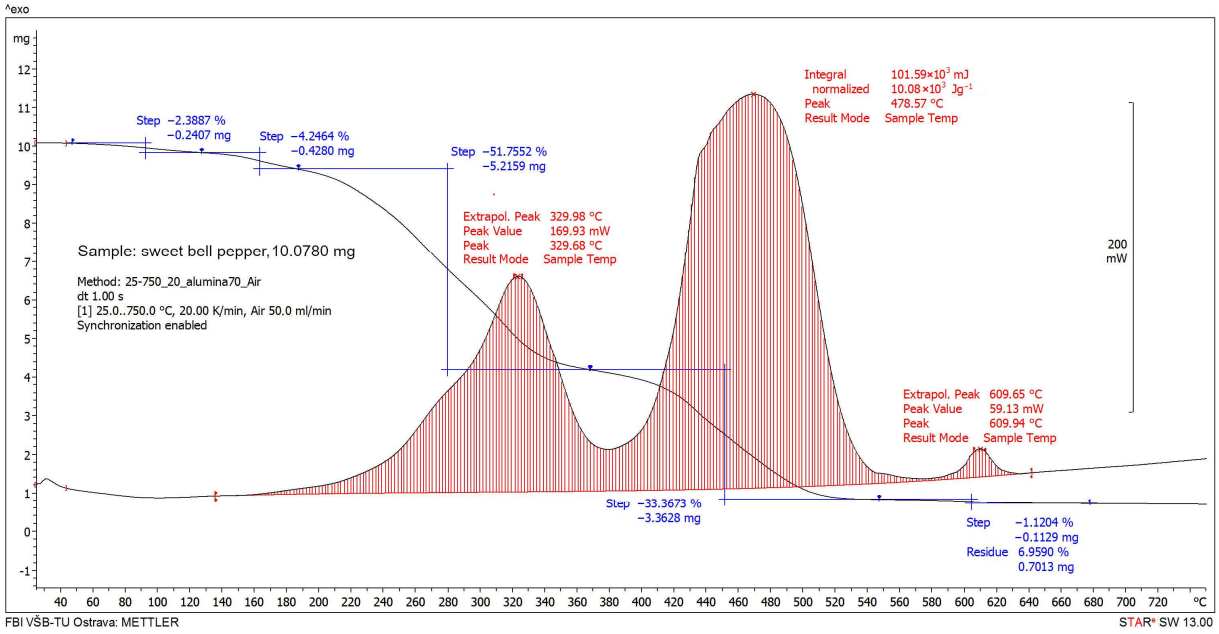


Figure 7. TG/DSC of Type I sample.

The thermal decomposition was carried out in two main phases. Initially, free water was released; then, bound water and other volatile compounds were released with increasing temperature. Between 160 and 200 °C, the rate of mass loss increased. The highest proportion of volatile substances was recorded for sweet peppers at more than 6.5%. The TGA results do not correspond to the data in Table 1. Above 200 °C, the decomposition

of the protein fraction and fats began, followed by the polysaccharides. Decomposition was mainly due to carbonisation; some of the gaseous products were oxidised in the air so that, from 180 °C onwards, the decomposition exhibited an exothermic colour. The exothermic maxima were around 330 °C. The heat evolution decreased as carbonisation continued. The minimum rate of mass loss was around 390 °C, where the minimum heat development in the phase of thermal decomposition also fell. From about 400 °C, the oxidation of the resulting carbonaceous residue began as the most energy-productive phase of decomposition. The maxima of heat evolution were between 478 and 504 °C and ranged from 93 to 101 J. In two pepper samples, a faint exothermic maximum was found at 600 °C, which could be related to the oxidation of the C-residue with a more ordered, thermally stable graphitic structure. The unburnable residue at 750 °C was between 6 and 7.5%.

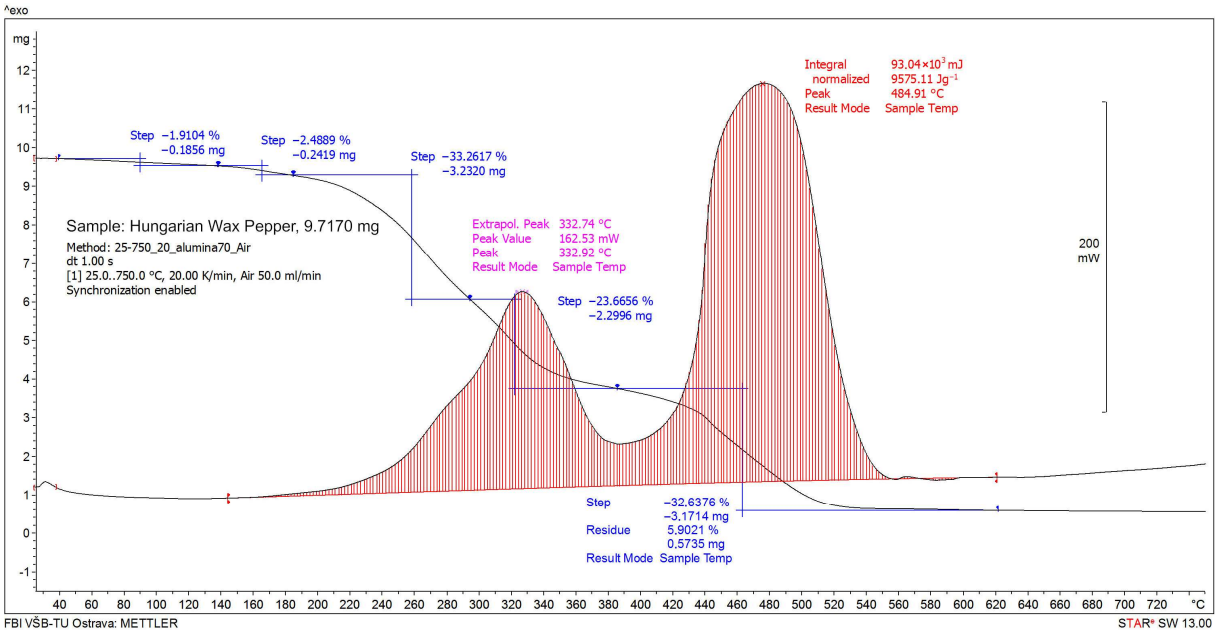


Figure 8. TG/DSC of Type II sample.

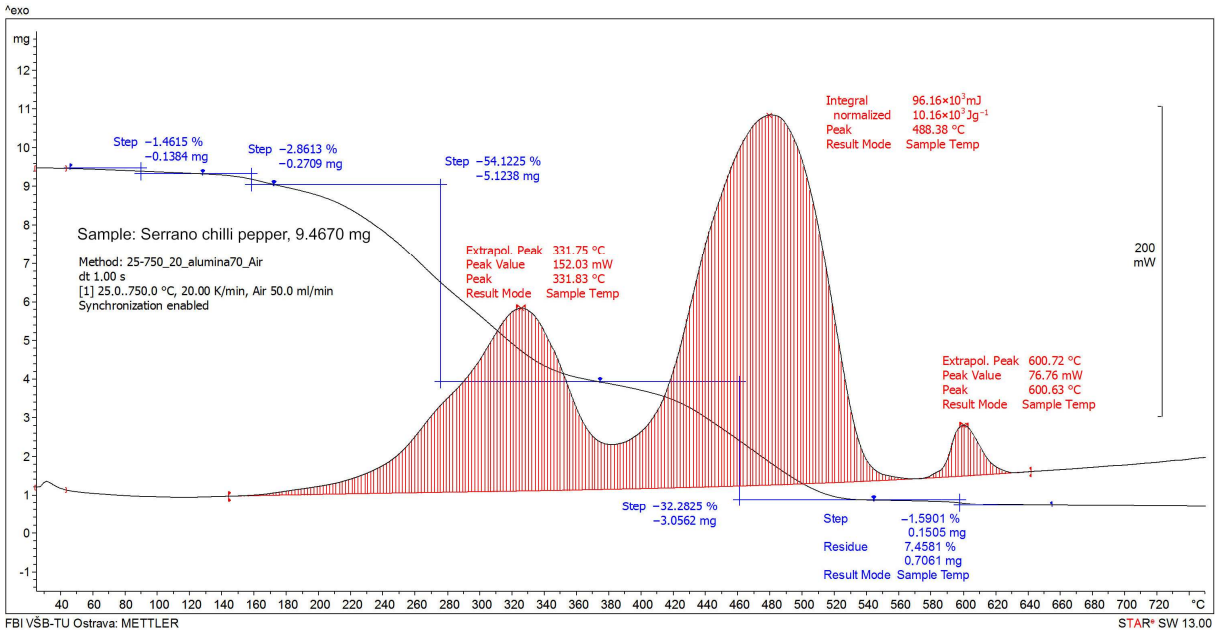


Figure 9. TG/DSC of Type III sample.

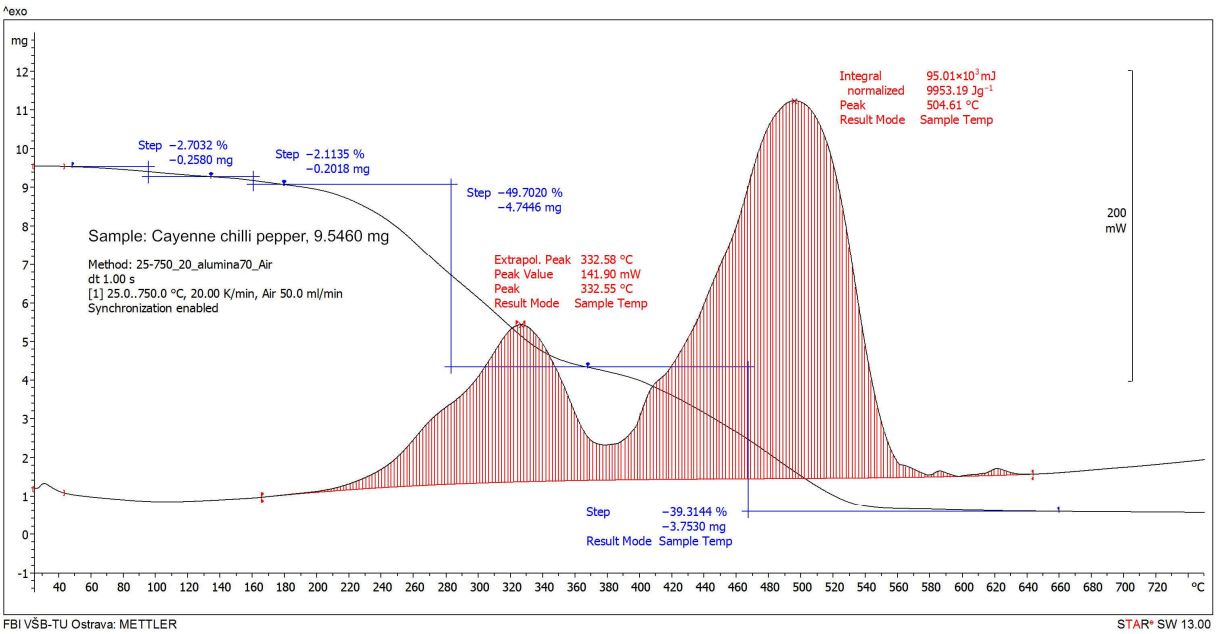


Figure 10. TG/DSC of Type IV sample.

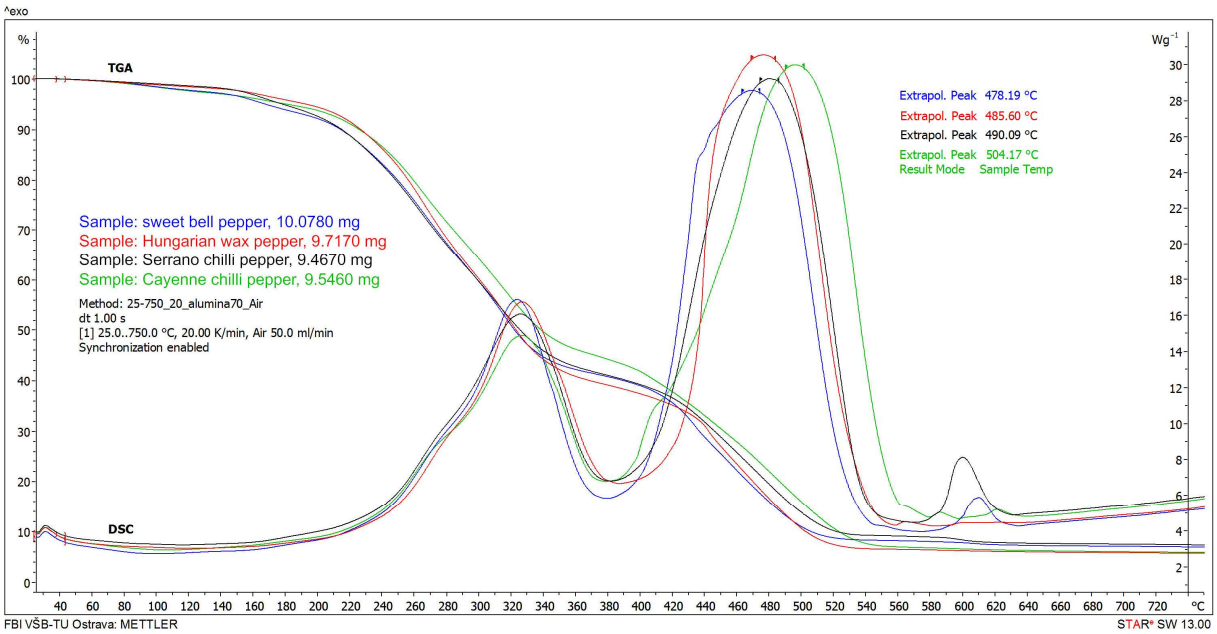


Figure 11. Comparison of TG/DSC records of pepper samples.

Pepper samples were tested to determine the minimum ignition temperature of the dust layer from a hot surface. The carbonisation of the sample with visible smouldering was considered an ignition. The results are shown in Table 5.

Table 5. Results of the minimum ignition temperature (MIT) of the dust layer of pepper samples.

Surface Temperature	Type I	Type II	Type III	Type IV
310 °C	-	-	-	-
320 °C	+	-	+	-
330 °C	+	+	+	-
340 °C	+	+	+	+

The minimum ignition temperatures of the pepper samples were measured within the range of 320–340 °C. Despite the fact that the samples ignited at different temperatures (with a max. difference of 20 K), we can conclude that the samples showed similar minimum ignition temperatures.

The results of the minimum ignition energy measurement are presented in Table 6.

Table 6. Minimum ignition energy (MIE) of pepper samples.

Spark Energy	Type I	Type II	Type III	Type IV
10 mJ	-	-	-	-
30 mJ	-	-	-	-
100 mJ	-	-	-	-
300 mJ	-	-	-	-
1000 mJ	+	+	+	+

The measured MIE results suggest that the type of pepper has no influence on the MIE energy values. The reason is that the MIE and MIT of the dust layer are limit values. The concentration usually has no significant effect on the limit values. The sample type does not yet have a significant impact on the values of the achieved boundary safety characteristics.

4. Conclusions

Based on the evaluation of the safety characteristics of different pepper samples, we can conclude that the type of pepper has a significant influence on certain safety characteristics.

Different varieties of pepper achieved different explosion characteristic values at the same measurement conditions. In this article, the maximum explosion pressure and the rate of pressure increase (explosion constant) were compared at various concentrations. Depending on the type of sample, the maximum explosion pressure and rate of pressure increase were achieved at the concentrations from 500 to 1500 $g \cdot m^{-3}$.

These results are important for explosion prevention. They illustrate that all types of samples should always be considered when designing explosion prevention in the industry. Therefore, explosion prevention must meet the entire range of concentrations.

The explosion characteristics are also influenced by the mechanism of action of the ignition cloud. Two explosion chambers with different volumes were used. Higher explosion characteristics (P_{max} + cca 0.5 bar and K_{st} cca 10–12 $bar \cdot m \cdot s^{-1}$) were achieved in the device of a smaller volume (20L). It was probably caused by the action of a cloud of ignition particles: so-called overdriving [19,20].

Different types of pepper have no effect on the safety characteristics used for secondary explosion protection, the minimum ignition temperature of the dust layer, and the minimum ignition energy.

Finally, food dust of partially different compositions can reach different safety characteristics. It is therefore necessary to take this fact into account when designing explosion prevention.

Author Contributions: L.K., Z.S. and R.K. conceived and designed the experiments; L.K., Z.S., R.K., S.H.S., M.M. and B.F. performed the experiments and analysed the data; R.K. and Z.S. managed all the experiments and writing process as the corresponding authors. All authors discussed the results and commented on the manuscript. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflicts of interest.

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