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Posted Date: 18 August 2023

doi: 10.20944/preprints202308.1307.v1

Keywords: hay, straw, radiant heat, ignition temperature

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Monitoring Ignition of Hay and Straw by Radiant Heat

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Abstract: Hay and straw are commonly used materials in agriculture. They are organic materials and therefore flammable. This article examines the behaviour of hay and straw when exposed to radiant heat. The objective of this study is to experimentally determine the ignition temperature of hay and straw under the influence of radiant heat. The research investigates the effects of sample type (hay and straw) and sample quantity on the thermal degradation process, temperature increase within the samples, and ignition temperature of the samples as a function of time. The ignition temperature of hay was determined to be higher (407°C) compared to straw (380°C). The results did not demonstrate a significant correlation between sample type and the thermal degradation process or the ignition temperature of hay and straw.

Keywords: hay; straw; radiant heat; ignition temperature

1. Introduction

Biomass as a renewable energy source is used as fuel [1–5], as a progressive natural insulation material in construction [6–8], and as animal feed and bedding in agriculture [9,10]. Hay and straw, which belong to the biomass group, are primarily utilized in agriculture [11,12]. For a cow weighing about 500 kilograms (look example Figure 1), more than 3 tons of hay will be required during the stay in the stable (from October to April) [13]. They are natural materials that are also used as natural thermal insulators [14–16]. However, it is necessary to acknowledge that these materials are flammable and not resistant to heat [17–19].

Figure 1. Demonstration of hay as feed for cows [13].

Their basis is the dried animal feed, which has a precise technological processing sequence, followed by packaging and storage [17]. The essence of the processing lies in drying and is based on the given moisture content (Table 1). The temperature increase is a consequence of the raw material processing by bacteria (fermentation) or the occurrence of decay. They both pose a fire hazard [18].

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Table 1. Group of Solid Fuels according to Decree 258/2007 Coll. [20].

Solid flammable substance	**Characteristics**	**Moisture**	**Storage** [17].
Dried animal feed (silage)	Mown green grasses Mown green legumes	more than 16% and up to 30% more than 16% and up to 35%	
Hay	Dried stem of grasses or legumes	Up to 16 %	Bales, Haystack, Hay loft, Barn, Hay shed
Straw	Dried stalk of cereal crops	-	

Hay is green forage preserved through natural drying or supplemental drying. In addition to fresh green forage - grass, hay is the most natural and suitable feed for all types of livestock [11,21]. Hay represents the dried stems of plants, preserved through drying and partial fermentation. Hay serves as a long-term supply of high-quality dry bulk feed if appropriately stored according to regulations [12]. It is a dried form of plant food, with water content ranging from 10-12% [22]. Once dried, the water content in hay decreases to 9-10% [11,12]. It is stored in hay lofts, which typically have a slatted floor with tunnels where heated ventilators blow air to expedite the drying process.

Straw is the dried stalk of cereal crops, obtained after the threshing. Straw typically consists of dried stalks of a single cereal crop. In Slovakia, barley, oat, wheat, and rye straw are commonly used [17]. Straw is most frequently used as bedding for livestock [9], as a substrate for mushroom cultivation [18], or as an insulating material [23,24]. All these types of straw have a tendency to self-ignite thermally and microbiologically [18]. The literature [22] states that straw is a flammable material that is easily ignited by sparks and hot surfaces.

Statistical data on fire incidents obtained from the Fire Technology and Expertise Institute of the Ministry of Interior of the Slovak Republic confirm the occurrence of fires in agriculture [25]. Although the number of fires shows a declining trend, agricultural fires maintain a relevant percentage share (11-5%) of the total annual fire incidents in the Slovak Republic [16].

The risk of fire in agricultural crops was considered when developing the Slovak standard [20]. Solid flammable substances (Table 1) include fodder, hay, straw, and other dry, mowed stem plants, solid fuels, extracted woody biomass, and woody biomass processed into various product assortments (timber, wood chips, sawdust, cellulose-based pellets and briquettes) (§2 of Decree 258/2007 Coll.) [20]. The potential ignition of hay and straw is dependent on external conditions. The critical parameter is the ignition temperature at which ignition occurs depending on the duration of the heat source's activity. Hot surfaces are part of technological elements used in agriculture. Their surface temperature can exceed the minimum ignition temperature and pose a risk of fire ignition.

The aim of the article is to experimentally determine the ignition temperature of hay and straw due to radiant heat. The influence of the sample type (hay and straw) and the selected sample mass (1, 2, and 3 g) on the course of the thermal degradation, temperature increase inside the sample, and ignition temperature over time were observed. Significant differences in thermal degradation and ignition temperature based on the type of fuel (hay and straw) were sought.

2. Materials and Methods

2.1. Experimental samples

For the purposes of the experiment, samples of hay and straw obtained from an agricultural farm were used (Table 2) [20].

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Table 2. Characteristics of samples.

Samples (Fodder)	Hay	Straw
Moisture (%) determined gravimetrically	11	10
Moisture (%) according to 258/2007 Act No. [20]	9-10	10
Sample before the experiment		

The samples were stored in bales and used for the operation of the cattle barn.

2.2. Experimental methods

The methodology consisted of two steps:

1. Monitoring the thermal degradation of samples based on gradual heating of the sample by radiant heat and tracking degradation points with identification of temperature and time during the degradation processes.
2. Determination of the minimum ignition temperature using isothermal testing using a hot-plate according to EN 50281-2-1:1998 [26].

In both cases, measurements were repeated 3 times.

2.2.1. Methodology for monitoring the thermal degradation of hay and straw

The experiment was carried out using a technical device called a hot-plate (Figure 2). Samples of hay and straw were subjected to gradual heating. The temperature of the heated plate and its increase over time were determined following the methodology described by Marková [16]. The obtained temperature-time curve [16] also served as the basis for measuring the ignition temperature according to EN 50281-2-1:1998 [26].

2.2.2. Determination of the minimum ignition temperature by isothermal heating using a hot-plate according to EN 50281-2-1:1998 [26]

The minimum ignition temperature of the organic layer was determined by isothermal heating of the sample placed on an electrically heated metal plate (Figure 2a, b). The minimum ignition temperature is defined as the lowest temperature of the heated plate's surface at which at least one of the following phenomena can be observed during the test:

1. Glowing, smouldering, or flaming combustion,
2. The temperature-time curve recorded by the thermocouple, which is placed at the centre of the sample layer, continuously rises with comparison to the temperature of the isothermally heated plate,
3. The temperature measured in the sample layer is 250°C higher than the temperature of the heated plate.

The experiment verified the occurrence of the first two phenomena described earlier. The minimum ignition temperature was determined for all samples (Figure 2 and Table 3).

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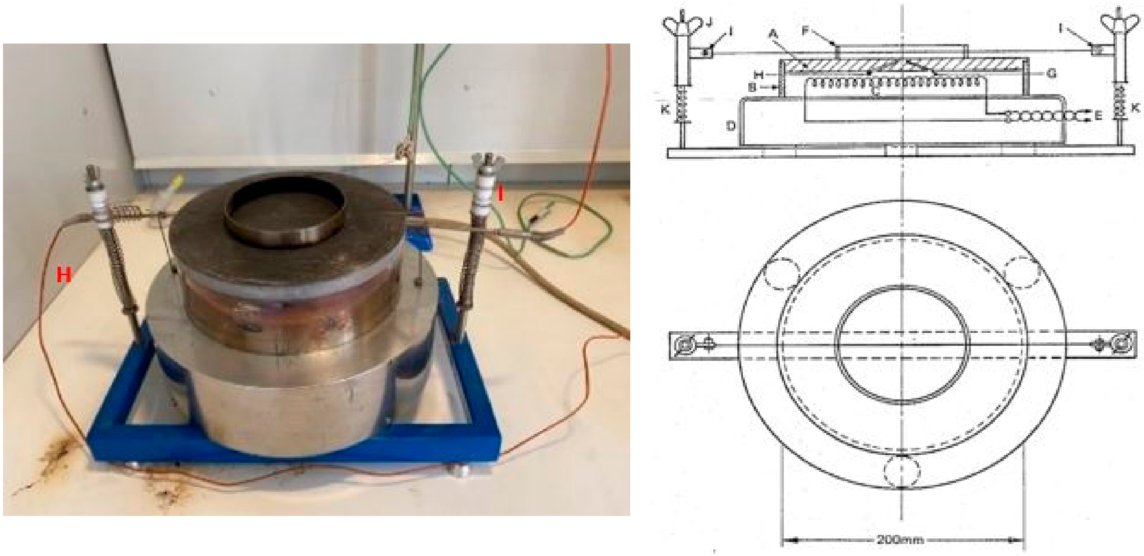


(a) (b)

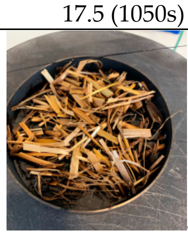
Figure 2. (a) Hot-plate device; (b) Scheme of the apparatus for determining the ignition temperatures of settled dust EN 50281-2-1:1998 [26]. Legend: A – heated plate, B – frame, C – heating element, D – base of the heating element, E – outlet for connecting the heating element to the power source and control, F – ring for creating the layer of dust, G – thermocouple in the plate for regulation, H – thermocouple in the plate for temperature recording, I – thermocouple for temperature recording in the layer of dust, J – height adjustment of the thermocouple using screws, K – spring.

A detailed description of individual steps of the experiment is provided by Balog et al. [27]. The experimental results were obtained using installed thermocouples which measured:

1. Surface temperature of the hot-plate Thot (marked by the red letter H in Figure 2a);
2. Temperature inside the hay (Thay) and straw (Tstraw) sample (marked by the red letter I in Figure 1a).

The weight (1, 2, and 3 g) and hence the thickness of the sample in the testing device hot-plate were gradually increased. The results identify changes in the sample by determining the temperature inside the sample, the temperature of the plate that caused the change, and the chronological sequence of events (Table 3).

Table 3.

Straw				
Process order	T_{straw} **(°C)**	t_{ex} **(min)/(s) ***	**Visual observations during measurement**	$T_{igniton}$ **°C**
1.	69.1	6 (360s)	Odour noted	
2.	91.4	8.5 (525s)	Smoking process appeared	
3.	142.6	11 (825s)	Carbonization of the lower stems of the tested sample	385.33±13.2
4.	145.2	16 (975s)	Carbonization of the edges of the tested sample, increasing smoke intensity	
5.	173.2	17.5 (1050s)	Ignition and formation of flames	
1 . 	2. 	3. 	4. 	5. 
Hay				

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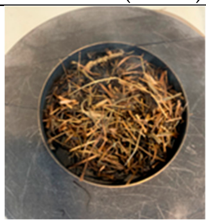
Process order	T_{hay} (°C)	t_{ex} (min)/(s) *	Visual observations during measurement	$T_{igniton}$ °C
1.	111.3	8 (480 s)	Smoke, thermal degradation	406.6±5.1
2.	160.8	13.5 (810 s)	Carbonization of the layer on the surface of the hot-plate	
3.	185.4	16.75 (1005s)	Carbonization of the edges of the samples and gradual degradation of the entire surface, smouldering process observed	
4.	192.6	18 (1080 s)	Ignition occurs	
	2. 	3. 	4. 	

* t_{ex} (min)/(s) – real experimental time, critical time, which identified steps of thermal degradation.

3. Results and Discussion

The conducted experiments provide interesting results. Description of the behaviour of the hay and straw layers during their thermal exposure to a radiant heat source is presented in Table 3. The moment of ignition is recorded as $T_{ignition}$ and T_{hot} in Table 4. The temperature values inside the samples are recorded as T_{hay} and T_{straw}. The data is supplemented with photographic documentation. The sample weight was continuously increased by 1g. The change in sample weight did not affect the course of the experiments, confirming the findings presented in Marková et al. [10,16]. Based on the repeated experiments, specific stages of the sample's behaviour during its thermal degradation were identified. These stages include the development of odour, smoking, carbonization of the bottom layer touching the hot-plate, carbonization of the sample edges, and ignition (Table 3, Table 4, and Table 5).

The course of thermal degradation of straw was more pronounced in identified stages compared to hay (Table 3).

The course of thermal degradation of hay and straw is significantly comparable. Differences arise in the thermal-time evaluation of their degradation (Table 3 and Table 4). The comparison is based on the generated temperature-time curves, i.e., the dependence of experimentally determined temperature (T_{hay} and T_{straw}) (Table 4) on time (Figure 3).

The ignition temperatures of hay and straw determined by two different procedures are significantly comparable (Table 4).

Experts are still debating which of the materials (hay & straw) poses a higher risk of fire ignition [28]. The results show an overall delayed process of thermal degradation for hay compared to straw at higher temperatures. The first phase of degradation (labelled as 1 hay and 1 straw in Figure 3) is characterized by odour. The odour of burning hay and straw starts at temperatures above 60°C, but with a 30-second delay for straw (Figure 3). The findings are consistent with the measures implemented in practice [17,28] and with regulation 258/2007 Coll [20]. Literature [17,28] presents a temperature of 65°C as the beginning of the dangerous thermal zone. The unpleasant odour intensified with increasing temperature in both types of samples.

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Table 4. Experimentally determined temperatures of hay and straw degradation processes as a function of time

Samples	Hay			Straw		
Monitored parameters	T_{hot} (°C)	T_{hay} (°C)	t_{ex} (s)	T_{hot} (°C)	T_{straw} (°C)	t_{ex} (s)
1. process: Odour	-	62.1±5.1	-	110-160	68.9±1.1	305±43.0
2. process: Smoke	220-280	105.9±5.2	505±69.9	160-200	97-5±5.8	454±61.5
3. process: Carbonization of the bottom layer of the sample	340-360	150.2±7.6	765±44.1	360-400	169.4±19.27	800±18.7
4. process: Carbonization of the edges of the sample	400-430	175.6±6.9	905±50.1	400-410	179.4±27.5	815±30.8
5. process: Ignition and burning	430-450	183.8±9.2	1050±24.5	410-430	189.9±25.6	960±63.6
Ignition temperature		406.6±5.1			385.33±13.2	
Ignition temperature according to EN 50281-2-1:1998 [26].		407			380	

* Tables may have a footer. Explanation of abbreviations: T_{hot} (°C) – temperature of the hot-plate surface, T_{hay} (°C) and T_{straw} (°C) – temperatures measured in the samples, t_{ex} (s) – real experimental time.

Smoke production was recorded at a temperature of 100°C inside the samples. The smoke had a white color. In terms of time, straw started smoking earlier, at 450 seconds. Hay started smoking at 505 seconds. As the surface and sample temperature increased, the smoking intensified (Figure 3).

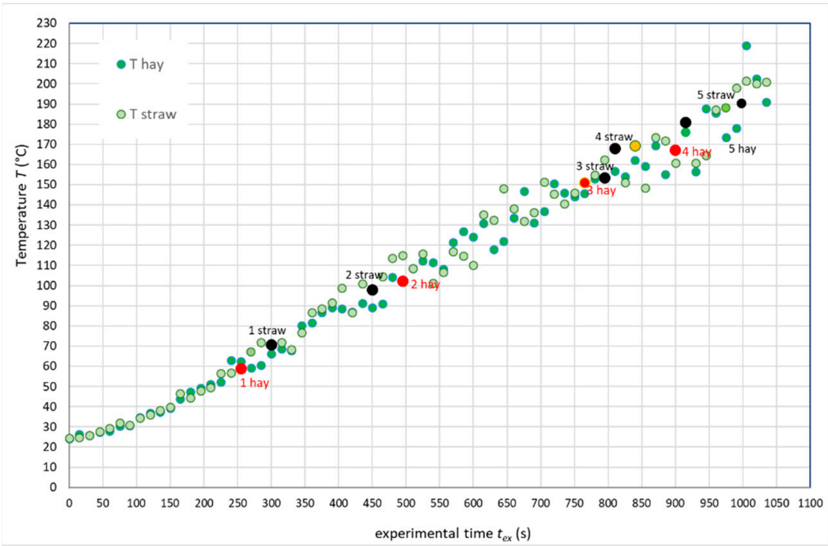

Figure 3. Temperature increase inside the samples of hay (T_{hay}) and straw (T_{straw}) as a function of time.

In the straw sample, carbonization of the bottom layer of straw stems occurred on average at a temperature of 169.4°C (Table 4) at 800 seconds. The carbonization process of the bottom layer of hay sample occurred at an average temperature of 150.2°C at 780 seconds (14 minutes) at a hot-plate temperature of 330.2°C. The carbonization process occurred in the edges of the straw sample at an average temperature of 175.6°C at 960 seconds (16 minutes) with the hot-plate temperature ranging from 360-400 °C. The 4th process begins earlier in straw (400-410 seconds) at a temperature of 179.4°C and a hot-plate temperature of 400-430 °C (Figure 4).

With the gradual increase in surface and sample temperature, the smoke intensified until the ignition point was reached, resulting in ignition in the tested straw sample. Subsequently, the smoke intensity decreased until it completely disappeared, leaving only glowing charred residues and stems of the tested samples (Figure 5), positioned 10 mm above the hot surface. here (Figure 4 and Table 2).

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(a) (b)

Figure 4. Samples after ignition (a) 2 g of hay sample, measurement at 1020 seconds; (b) 2 g of straw sample, measurement at 1050 seconds.

Throughout the entire degradation process, the critical temperatures of hay and straw were comparable, with hay showing degradation at an earlier stage and at lower temperatures compared to straw. Subsequent events occurred earlier in straw and at lower temperatures than in hay. The risk of fire cannot be considered higher for hay or straw, in terms of the time-related development of thermal degradation or temperatures of thermal degradation in partial processes (Figure 3, Table 4).

The literature [22] states a critical temperature of 80°C at which the spontaneous combustion process of hay and straw occurs. Several authors [3,7] report a higher risk of fire for hay compared to straw. The authors [17] attribute this to the increase in the internal temperature of the hay bale, which does not decrease but, on the contrary, creates an ideal environment for the proliferation of thermophilic bacteria. Consequently, the temperature of the hay bale rises up to 77°C (reported as the temperature of spontaneous combustion) [17].

The determined experimental results of ignition temperatures are higher for straw. Flachbart and Svetlík [29] also present higher ignition temperature values for straw (Table 5). The ignition temperatures of hay and straw samples (Table 2) show differences in values.

Table 5. Mutual comparison Ignition temperatures of hay and straw

Ignition temperature	**Hay**	**Straw**
Experimentally determined temperature (°C)	406.6±5.1	385.33±13.2
Temperature experimentally determined according to EN 50281-2-1:1998 [26] (°C)	407	380
Temperature according by [18]	310	330
Temperature according to [29]	230	310

The search for a significant effect was performed using the statistical program Qplot. Produced histograms (box plots) did not confirm a significant influence of weight and sample type on the minimum ignition temperature of hay and straw (Figure 5a), as well as on the time-related development of thermal degradation of the samples (Figure 5b).

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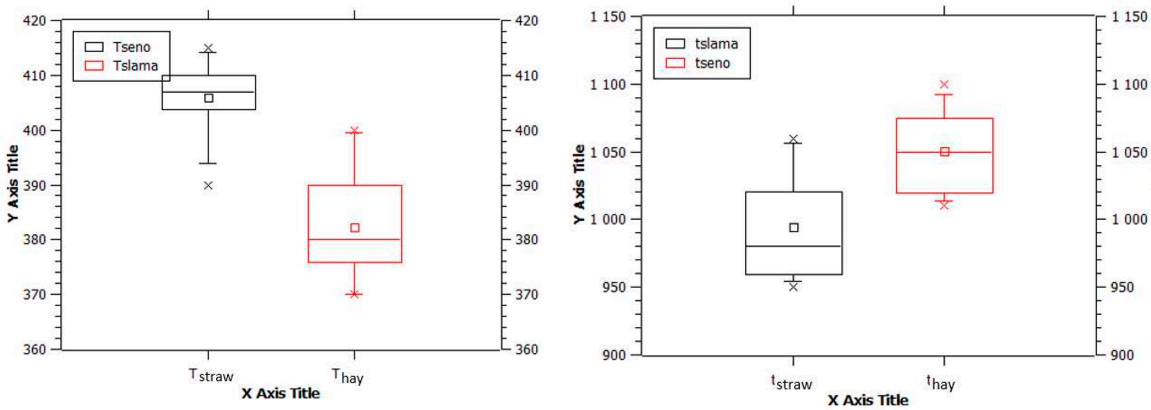

(a) (b)

Figure 5. Box plots - graphical dependencies. (a) of wood species and weight on the minimum ignition temperature; (b) of wood species on the time course of the thermal degradation.

Box plots (Fig.5) show faster straw degradation at lower temperatures than hay.

The thermal degradation of hay can be compared with the research of Xie et a. [30]. TGA-DTG-DSC curves of rape straw under a heating rate at 10°C.min^{-1} (Figure 6) identify comparable temperatures of thermal degradation of the hay with our experimental results.

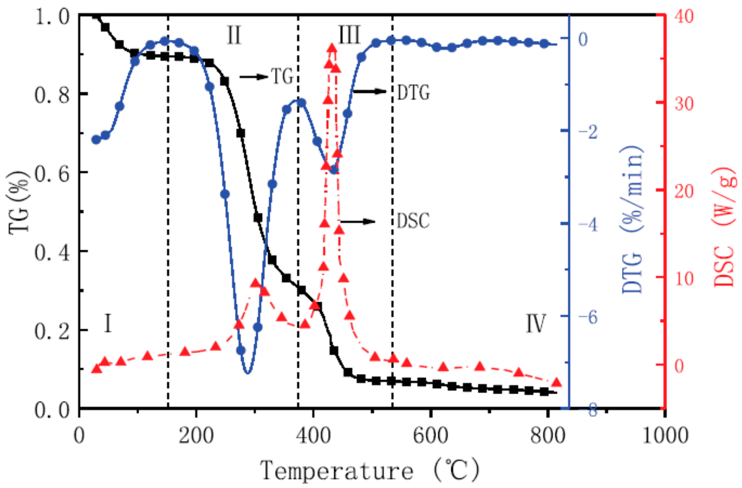

Figure 6. TGA-DTA-DSC curves of rape straw under a heating rate at 10°C.min^{-1} [30]

4. Conclusions

Based on the obtained experimental results:

- The minimum ignition temperature of hay according to EN 50281-2-1:1998 [26] is 407°C.
- During exposure to radiant heat, the critical temperatures of hay and straw were comparable, except for the initial phase, where hay degradation started earlier at a lower temperature and in a shorter time interval compared to straw.
- It is not possible to unequivocally determine which of the mentioned materials poses a greater risk of fire.
- The significant effect of weight and sample type on the minimum ignition temperature of hay and straw, as well as on the time-related development of thermal degradation of the samples, was not confirmed.

Author Contributions: Conceptualization, I.M. and I.T.; methodology, Z.G.; software, I.M.; validation, I.T., I.M. and Z.G.; formal analysis, J.J.; investigation, Z.G. and M.I.; resources, I.T., J.J. and M.I.; data cu-ration, I.M, J.J.; writing—original draft preparation, I.M.; writing—review and editing, J.J.; I.T.; project administration, J.J.; funding acquisition, I.M. All authors have read and agreed to the published version of the manuscript.

Funding: This article was supported by Institute Grant of University of Žilina No 12716

Data Availability Statement: Not applicable for studies not involving humans or animals.

Acknowledgments: This article was supported by the Institute Grant of University of Žilina No 12716.

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

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