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Effect of radiant heat on straw

Introduction

Straw is the dry, aboveground part of cereals that has been deseeded (Decree 258/2007 Coll.). It is made up of the dried stalks of only one cereal. Straw has been used since time immemorial in agriculture and construction (Cascone et al., 2019). The main feed for cattle is still straw (Jagaba, 2022; Zhou, 2022). Significant research attention has been paid to the safe storage of these materials (Winans, 2014; Boltianskyi et al., 2021; Brown, Henry, 2022; Du et al., 2022; Liu, 2023) and their transport to livestock (Cheng, 2022; Rajabnia, 2023). Most research on hay and straw focuses on sanitation (Shipton, 2011; Glatter, et al., 2021) and food safety (Wang et al., 2022). However, the development of the above industries has brought additional uses for straw.

Barley, oat, wheat and rye straw are used in Slovakia (Sraková et al., 2008). It is becoming a progressive building material (Vavrínová et al., 2021), an insulation material (Makovická et al., 2015; Kadlicová, 2016), a material for reinforcing (reinforced) polypropylene composites (Yang, Hu, 2015), and a substrate for mushroom cultivation (Zhao et al., 2021). At the same time, straw is evaluated as a natural waste (Jameel, Keshwani, 2017) and straw is processed for secondary use (Nielsen, Blinksbjerg, 1989) – Tab. 1. Second generation biofuels from lignocellulosic feedstocks are part of a suite of solutions for peak oil utilisation and a secure climate economy (Ellem, Mulligan, 2012). The above trend persists and straw is used as fuel (Jameel, Keshwani, 2017; Ai et al., 2021; Turkyilmazoglu, 2021; Zhou, 2022; Liu, 2023). Straw is used as a weeding material, and a dry by-product with fine grains is commonly used. It is easy to handle, carbonaceous for a compost pile, and readily available in most areas (*BDLE*, 2008). Last but not least, straw is used as bedding for cattle in pure form (Johanssen et al., 2018) or in combination with other materials (Giertlová et al., 2023). One of the crucial factors in maintaining a healthy dairy herd is having sanitary animal bedding. With bedding being one of the primary sources of exposure to environmental mastitis pathogens, the management of this material is important in maintaining herd health and the economic vitality of the farm. Smith et al. (2017) describe basic bedding materials used in New England. Traditional dairy farmers use solid manure (MNS; complex or digested) and hay as the primary bedding materials, sawdust, sand and hay, respectively. Straw, wood shavings, and wood chips, woody bedding were also used, but less than primary bedding materials.

Tab. 1. Use of biomass as a source for energy production (Jameel, Keshwani, 2017)

Origin	Source of biomass
special energy crops	grown specifically for bioenergy production
residues from cultivated crops	are corn stalks, rice and wheat straw, bagasse (sugar cane residue) and even vine cuttings
crop residues	which form part of the crop that is discarded after the useful products of the harvest have been extracted
agricultural residues yard waste	consists of grass clippings, leaves and tree trimmings
municipal waste	mostly consists of waste paper, plastics, food waste and other non-combustible material.
from other wastes	which are traditionally thrown away and have no apparent value

Adam et al. (2021) wrote that post-harvest rice waste was abundant and had no commercial value or significant use in Malaysia. This paddy waste is commonly burnt on the landfilled which causes open firing and leads to an environmental problem. This study determined the potential of rice straw waste for charcoal briquette production and investigated the effect of using different binders (cornstarch and tapioca) in briquette production. All of straw species are prone to thermal and microbiological spontaneous combustion (Giertlová et al., 2023). Literature (*Tables of Flammable and Hazardous Substances*, 1980) states that straw is a flammable substance that is easily ignited by sparks and hot surfaces.

The essence of the processing of straw lies in drying and is based on the given moisture content (Tab. 2). Their basis is the dried animal feed, which has a precise technological processing sequence, followed by packaging and storage (*BORGA*, 2022). The temperature increase is a consequence of the raw material processing by bacteria (fermentation) or the occurrence of decomposition. They both pose a fire hazard (*FReSH*, 2012).

Tab. 2. Group of Solid Fuels according to Decree 258/2007 Coll.

Solid flammable substance	Characteristics	Storage (according *BORGA*, 2022)
Dried animal feed (silage)	Straw	
Straw	Dried stalk of cereal crops	Bales, Haystack, Hay loft, Barn, Hay shed

Availability of water is a critical factor for microorganisms to function (Madigan et al., 2000); lack of available water on solid substrates is a significant source of microbial stress (Griffin, 1981; Gervais et al., 1996). Microorganisms need water for motility and transportation of nutrients to cells and waste products away from cells (Madigan et al., 2000; Richard et al., 2002). Native microbial activity in hay and other agricultural residues has been studied extensively in the context of self-heating to the point of spontaneous combustion. Many of these studies have noted the importance of available moisture. For example, in hay, little or no microbial activity is expected below 25% to 30% on a wet basis (w.b.) (Rothbaum, 1963; Festenstein et al., 1965; Bowes, 1984). Higher moisture contents should be conducive to more microbial activity because more bacteria would be able to thrive. In hay that was allowed to self-heat, the maximum temperature of a bale increased with increasing initial moisture content (Rothbaum, 1963). The increased ability to self-heat hay was attributed to higher levels of microbial activity.

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 (*STATdat*, 2022). Although the number of fires shows a declining trend, agricultural fires maintain a relevant percentage share (5–11%) of the total annual fire incidents in the Slovak Republic (*STATdat*, 2022). The risk of fire in agricultural crops was considered when developing the Slovak standard (Decree 258/2007 Coll.). Solid flammable substances (Tab. 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.). 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 this study is to find out, through experiment, how straw (plant stemlike material) will behave in contact with an initiating hot surface source. This is a very important issue because fires in warehouses of tested materials result in damage to property, animal lives, and in the worst case, human casualties.

Material and Methods

Experimental samples

For the purpose of the experiment oat straw was used. The research material was obtained from a farm. This material was fragmented into smaller pieces (Fig. 1).

Fig. 1. Samples “straw 2“ before experiment (Photo. J. Jaďuďová)

The most important parameters of this experiment are summarised below (Tab. 3).

Tab. 3. Characteristics of samples and experimental conditions

Samples (Fodder): Straw	
Moisture determined gravimetrically	10 (%)
Moisture according to Decree 258/2007 Coll.	10 (%)
Density	0.11 (g.cm^{-3})
Conditions of experiments in digester	
Air moisture	54 (%)
Temperature	23.5 (°C)
Area of Heat Load	78.54 (cm^{2})

Experimental methods

The methodology has of two parts. The first part is monitoring the thermal degradation of straw samples based on the thermal load of the sample using radiant heat and tracking the thermal degradation with identification of the temperature and duration of the degradation processes. The second part is determination of the minimum ignition temperature of straw samples by isothermal tests on a hot plate in accordance with the EN 50281-2-1:1998 standard. In both cases, measurements were repeated 3 times for 2, 2.5 and 3 g weight of samples.

Methodology for monitoring the thermal degradation of hay and straw

The experiment was carried out using a technical device called a hot-plate (Fig. 2).

Fig. 2. Hot-plate device; H – thermocouple in the plate for temperature recording, I – thermocouple for temperature recording in the layer of dust (Photo. J. Jaďuďová)

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 et al. (2022). The obtained temperature-time curve (Fig. 3) also served as the basis for measuring the ignition temperature according to EN 50281-2-1:1998.

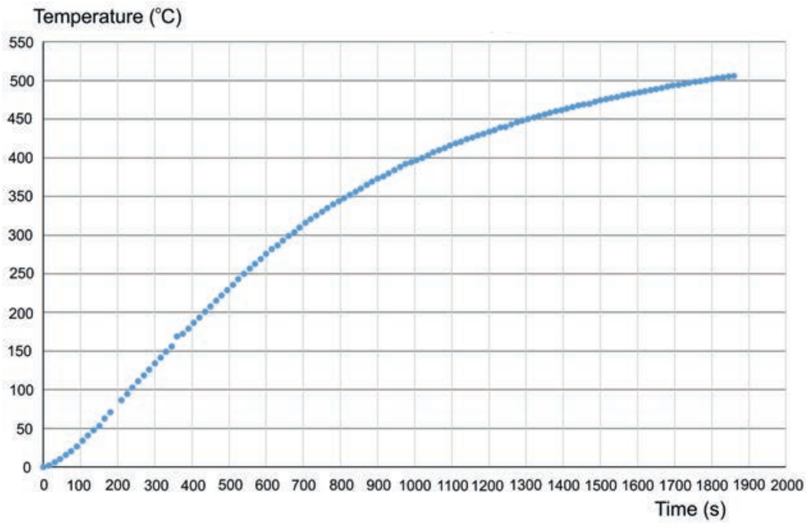

Fig. 3. Temperature-time curve according to EN 50281-2-1:1998

Determination of the minimum ignition temperature by isothermal heating using a hot-plate

The minimum ignition temperature of the organic layer was determined by isothermal heating of the sample placed on an electrically heated metal plate (Fig. 2). 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: glowing, smouldering, or flaming combustion. 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. 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 (Fig. 2). A detailed description of individual steps of the experiment is provided by Balog et al. (2014). One thermal thermocouple measures the actual temperature of the heated metal plate and second thermal thermocouple measures the temperature of tested sample, which is located 5 mm above the plate. The experimental results were obtained using installed thermocouples which measured: surface temperature of the hot-plate Thot (marked by the red letter H in figure 2), temperature inside the hay (T_{hay}) and straw (T_{straw}) sample (marked by the red letter I in figure 2). 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.

Results and discussion

The conducted experiments provides 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 (4).

Tab. 4. Description and quantification processes of thermal straw degradation

Straw samples	Mass (g)	T_{ign} (°C)	T_{straw} (°C)	Visual observations during measurement
straw 1	2	407	69.1	360 s (6 min) odour recorded
			91.4	at 525 s (8.5 min) a fuming process occurred in the sample
			14.6	at 825 s (11 min) charring of the lower stems of the test sample occurred
			145.2	at 975 s (16 min) charring of the edges of the test sample occurred, the smoke intensity increased
			173.2	At 1050 s (17.5 min) the ignition point occurred and the first outbreaks began to form.

straw 2	2.5	376	67.5	in 300 s (5 min) odour recorded
			95.8	at 465 s (7.5 min) a fuming process occurred in the sample
			178.5°	at 795 s (13 min) charring of the lower stems of the test sample occurred
			180.4	at 870 s (14.5 min) the edges of the sample also charred
			170.5	at 915 s (15 min) the ignition point occurred and the first foci began to form
straw 3	3	376	70.3	at 255 s (4 min) odour detected
			105.3	at 375 s (6 min) a fuming process occurred in the sample
			187.1	at 780 s (13 min) charring of the lower stems of the test sample occurred
			212.7	at 870 s (14.5 min) charring of the edges of the test sample occurred, the smoke intensity increased
			226.2	at 915 s (15 min) the ignition point occurred and the first foci began to form

* Explanation of abbreviations: T_{ign} – temperature of ignition, T_{hot} – temperature of the hot-plate surface, T_{straw} – temperatures measured in the samples

In the straw sample, carbonisation of the bottom layer of straw stems occurred on average at a temperature of 169.4°C (Tab. 4) for800 seconds (s). The carbonisation process of the bottom layer of hay sample occurred at an average temperature of 150.2°C for 780 s (14 minutes) at a hot-plate temperature of 330.2°C. The carbonisation process occurred in the edges of the straw sample at an average temperature of 175.6°C for 960 s (16 minutes) with the hot-plate temperature ranging from 360–400°C. The 4th process begins earlier in straw (400–410 s) at a temperature of 179.4°C and a hot-plate temperature of 400–430°C (Fig. 4).

Tab. 5. Experimentally determined temperatures of straw degradation processes as a function of time; values and standard deviations (± SD) are given

Processes		Monitored parameters		
		T_{hot} (°C)	T_{straw} (°C)	t_{ex} (s)
1.	Odour	110–160	68.9 ±1.1	305 ±43.0
2.	Smoke	160–200	97.5 ±5.8	454 ±61.5
3.	Carbonisation of the bottom layer of the sample	360–400	169.4 ±19.27	800 ±18.7
4.	Carbonisation of the edges of the sample	400–410	179.4 ±27.5	815 ±30.8
5.	Ignition and burning	410–430	189.9 ±25.6	960 ±63.6
	Ignition temperature	385.33 ±13.2		
	Ignition temperature according by EN 50281-2-1:1998	380		

* Explanation of abbreviations: T_{hot} – temperature of the hot-plate surface, T_{straw} – temperatures measured in the samples, t_{ex} (s) – real experimental time, colours are points in Fig. 5

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

Fig. 4. Samples during thermal degradation and ignition straw's samples; A – measurement in 525 s (8.5 min), 2 g of sample; B – measurement in 825 s (11 min), 2 g of sample; C – measurement in 975 s (16 min), 2 g of sample; D – measurement in 465 s (7.5 min), with a sample mass of 2.5 g, E – measurement in 795 s (13 min), with a sample mass of 2.5 g, F – measurement in 870 s (14.5 min), with a sample mass of 2.5 g, G – measurement at 375 s (6 min), with a sample mass of 3 g; H – measurement at 870 s (14.5 min), with a sample mass of 3 g, I – measurement at 915 s (15 min), with a sample mass of 3 g (Photo. J. Jaďuďová, I. Marková)

glowing charred residues and stems of the tested samples (Fig. 5), positioned 10 mm above the hot surface here (Fig. 4). All the processes that occurred during the thermal loading of the samples with radiant heat are odour, fuming, charring of the bottom layer and edges, and ignition point are summarised in table (5) and shown in figure (5) – colour-coded in the time-temperature curves. Straw is a heterogeneous material. The given property was also shows in the experiments. The three experiments present

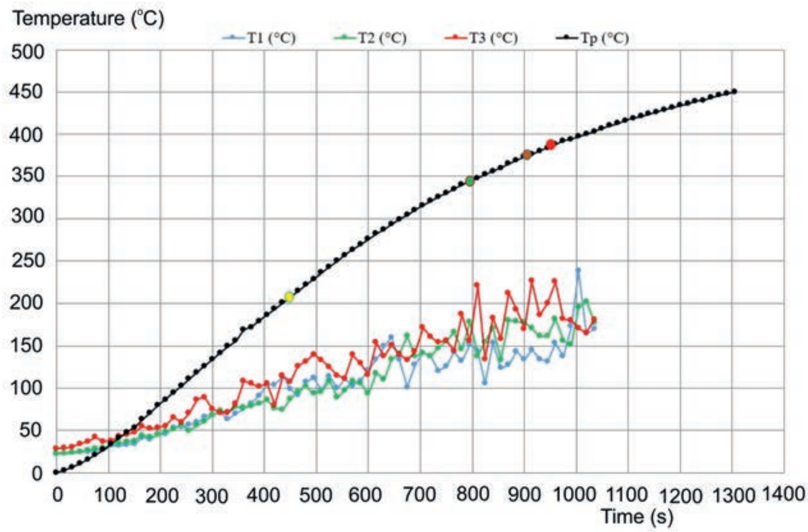

Fig. 5. Heating curves over time based on average thermal degradation temperatures of straw samples; legend: black curve- hot-plate surface temperature values obtained by calibration of the equipment (Tp): yellow oval – smoking process, green oval – charring of the sample bottom layer, brown oval – charring of the sample edges, red oval – point of ignition temperature; T1, T2, T3 – heat-time curves of straw sample 1, 2 and 3

the same thermal degradation processes with deviations of the temperature values. The T_{hot} value is presented as the temperature range on the hotplate in which the selected process was carried out (odour, smoke, carbonisation of the bottom layer of the sample, carbonisation of the sample edges, ignition and combustion). The T_{straw} values are the critical temperatures in the straw's samples when that process started. The resulting standard deviations (± SD) are evidence of the heterogeneity of the material but also indicate the general character of the thermal degradation process of straw. The highest variance of the obtained values of T_{straw} (179.4 ±27.5) and t_{ex} (815 ±30.8) was in the process of carbonisation of the sample edges (Tab. 5).

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 (Fig. 3, Tab. 4).

The literature (*Tables of Flammable and Dangerous Substances*, 1980) states a critical temperature of 80°C at which the spontaneous combustion process of hay and straw occurs. Several authors (Martiník, 2014; Tobias, Writer, 2021) report a higher risk of fire for hay compared to straw. The authors 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) (*BORGA*, 2022). The determined experimental results of ignition temperatures are higher for straw. Flachbart and Svetlík (2018) also present higher ignition temperature values for straw (Tab. 5). The ignition temperatures of hay and straw samples (Tab. 2) show differences in values. The ignition point of straw is given as 310°C (*Tables of Flammable and Dangerous Substances*, 1980). The experimentally obtained average value (Tab. 6) is 385.3°C.

Tab. 6. Mutual comparison Ignition temperatures of straw (°C)

Ignition temperature	Straw
Experimentally determined temperature	385.33, SD ±13.2
Temperature according by (*FReSH*, 2012)	330
Temperature according by (Flachbart, Svetlík, 2018)	310
Temperature experimentally determined according to EN 50281-2-1:1998	380

Conclusions

Based on the obtained experimental results: [1] the minimum ignition temperature of straw according to EN 50281-2-1:1998 is 380°C, [2] the ignition temperature of the straw was obtained by continuous release of radiant heat on the heating plate and was 385.3°C, [3] process thermal straw degradation need relatively longer time and higher ignition temperature, [4] value of ignition depends on conditions of experiments. The obtained results of the minimal initiation temperature have a higher value (380°C) than the results of other authors (around 310°C). These results can be considered as surprising result at this moment. The higher the initiation value of the natural material, the lower the risk of fire. Existing previous studies on this topic have primarily focused on investigating the impact of different forms of bedding materials on the living conditions of livestock. In this experiment, we analysed the fire-technical properties of straw as an alternative form of bedding. We are aware of some limitations of this study. First, the study was conducted on a small number of samples obtained from an agricultural farm. Second, we used only one initiation source (radiant heat). The contribution's innovation is the original experimental data of thermal straw degradation.

Conflict of interest

The authors declare no conflict of interest related to this article.

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Abstract

The straw is mostly used in agriculture as fodder or bedding for livestock. It is a natural organic material, i.e. flammable. This article deals with the observation of the behaviour of straw when heat loaded to radiant heat. The aim of the article is to experimentally determine the ignition temperature of straw as a function of the time of exposure to radiant heat. At the same time, the minimum ignition temperature of straw samples was determined using isothermal tests on a heating plate in accordance with the EN 50281-2-1:1998 standard. The influence of a selected amount of straw sample on the thermal degradation behaviour, the temperature increase inside the sample and the ignition temperature of the sample as a function of time were observed. Straw degradation processes (at temperature °C) were identified as a function of time: odour, smoke, charring of the lower layer of the sample, charring of the edges of the sample, ignition and burning. The value of the straw ignition temperature 380°C is sufficient for the initiation and development of fire.

Keywords: straw, radiant heat, ignition temperature

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Wpływ promieniowania cieplnego na słomę

Streszczenie

Wykorzystanie słomy jest bardzo zróżnicowane. Jednak najczęściej jest ona używana w rolnictwie jako pasza lub ściółka dla zwierząt gospodarskich. Słoma jest materiałem organicznym, czyli bardzo łatwopalnym. W artykule przedstawiono eksperyment obrazujący wpływ ciepła promieniowania na słomę. Głównym celem było doświadczalne wyznaczenie temperatury zapłonu słomy w funkcji czasu oddziaływania ciepła radiacyjnego. Zaobserwowano wpływ wybranej ilości próbki słomy na przebieg degradacji termicznej, wzrost temperatury wewnątrz próbki oraz temperaturę zapłonu próbki. Zidentyfikowano procesy degradacji słomy pod wpływem temperatury w funkcji czasu: zapach, dym, zwęglenie dolnej warstwy próbki, zwęglenie krawędzi próbki, zapłon i spalenie. Do zainicjowania i rozwoju spalania słomy wystarczająca jest wartość temperatury zapłonu 380°C.

Słowa kluczowe: słoma, ciepło promieniowania, temperatura zapłonu

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