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FIRE AND EXPLOSION CHARACTERISTICS OF ENERGY WILLOW BIOMASS DURING THE SUPERHEATED STEAM DRYING PROCESS

Abstract

In this paper the explosive and fire properties of energy willow dust were experimentally determined before and after drying with superheated steam at temperatures of 120°C, 140°C, 160°C and 180°C. The conducted research has shown that operating parameters of the installation of drying with superheated steam of the energy willow biomass have a decisive impact on the fire-explosive characteristics of the dust produced. The results indicate that the higher the drying temperature, the stronger the probability of ignition of the willow dust cloud, the faster the flame propagation and the higher the explosion intensity. Although the superheated steam drying installation for energy willow biomass is considered to be safe, the probability of occurrence of a fire or explosion events of the biomass dust-air mixture is likely.

Keywords: woody biomass, superheated steam, combustible dust, explosive dust, energy willow

CHARAKTERYSTYKA POŻAROWO-WYBUCHOWA BIOMASY WIERZBY ENERGETYCZNEJ W PROCESIE SUSZENIA PARĄ PRZEGRZANĄ

Abstrakt

W artykule wyznaczono eksperymentalnie właściwości wybuchowe i pożarowe pyłu wierzby energetycznej przed i po suszeniu parą przegrzaną w temperaturach 120°C, 140°C, 160°C i 180°C. Na podstawie przeprowadzonych badań stwierdzono, że parametry pracy instalacji suszenia parą przegrzaną biomasy wierzby energetycznej mają decydujący wpływ na charakterystykę pożarowo-wybuchową powstającego pyłu. Wyniki wskazują, że im wyższa temperatura suszenia, tym większe prawdopodobieństwo zapłonu chmury pyłu wierzby, tym szybsze rozprzestrzenianie się płomienia i większa intensywność wybuchu. Pomimo, że instalacja suszenia parą przegrzaną biomasy wierzby energetycznej jest uważana za bezpieczną to prawdopodobieństwo wystąpienia zdarzeń pożarowych lub wybuchowych mieszaniny pyłowo-powietrznej biomasy jest prawdopodobne.

Słowa kluczowe: biomasa drzewna, para przegrzana, pył palny, pył wybuchowy, wierzba energetyczna

1. Introduction

One of the elements of the policy aiming to reduce CO2 emissions (20% by 2020, 40% by 2030, 60% by 2040 and 80% by 2050) is the use of biomass as a renewable energy source. The energy willow is one of the promising plants which, similarly as the common reed, multiflora rose, Jerusalem artichoke or Pennsylvania sida, can be used for energy purposes. This plant is easy to grow, has a high yield potential per unit area of land and can be grown on the same rootstock for 25 to 30 years. The problem is the relatively high moisture content of the raw willow, which causes it to increase in weight and decrease in calorific value [1]. This also increases the cost of transporting biomass from the place of its acquisition to the place of combustion. Another extremely important problem is its variability, which depends on the seasoning period (thanks to seasoning, the calorific value of energy crops can be increased), which results in a low calorific value and changes. Changes in weather conditions before and at the time of harvesting energy crops from fields have a very significant impact on their moisture content. One of the known methods meant to increase the calorific value of willow is drying with uperheated steam. It involves removing or reducing water contained in the material, which reduces the moisture content of the biomass from 50-60% to 10-15% and increases the calorific value from 5–8 MJ/kg to 15–20 MJ/kg [2]. The advantages of superheated steam drying of materials include: an anaerobic atmosphere in the system, obtaining sterile material that ensures a high durability of the fuel obtained and the ease of energy recovery compared to convective air or flue gas drying [3–7]. However, the preparation of material by grinding and storing prior to the drying process, as well as of the dried material, can cause numerous fire and explosion hazards [8]. Inside the drying installation, where the dried material is in contact with steam, the fire/explosion hazard is minimised (this is in accordance with the principles of inherent safety), but outside the internal part of the drying installation, due to the considerable fragmentation of the dried material, it may involve an explosion hazard. With the dynamic development of technologies for processing and drying of woody biomass, a significant increase in fires and explosions of dust-air mixtures can be observed, as well as an increase in human, material and environmental losses [8–11]. In order to prevent and limit the consequences of such incidents, to optimise the superheated steam drying technology and to correctly select innovative explosion protection systems [12–13], knowledge of the fire and explosion parameters of energy willow dust before and after the superheated steam drying process is necessary.

2. Description of study material and methods

The material used in the study was energy willow (Salix Viminalis), obtained from a 3-year plantation located in central Poland, next to the sewage treatment plant in Łódź. Before starting the experiments, chips (10–15 × 8 × 3mm) were prepared from fresh willow shoots (2 m long, 30 mm in diameter). Experimental studies related to the drying of energy willow with the use of superheated steam were carried out in four temperature ranges, i.e. 120°C, 140°C, 160°C and 180°C using test equipment (Figure 1) built at the Technical University of Lodz [1]. The

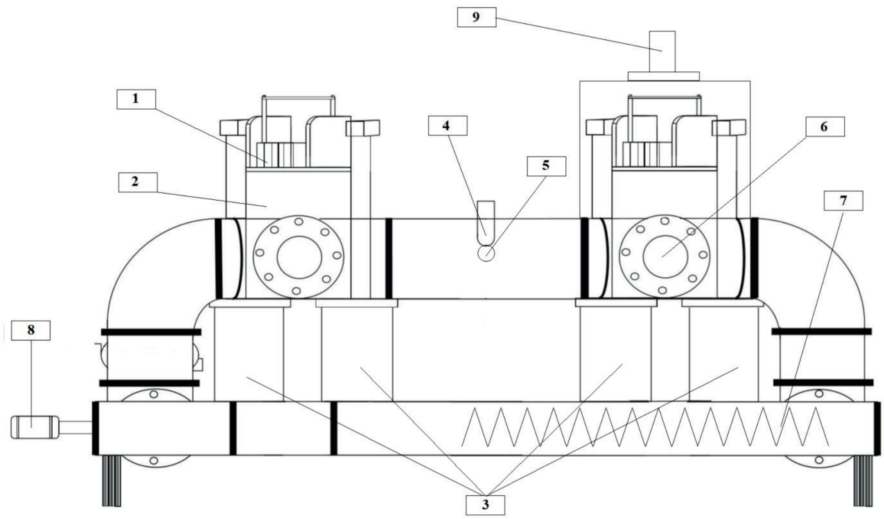


Fig. 1. Diagram of apparatus for the determination of drying kinetics in superheated steam: 1-closure, 2-measuring chamber, 3-actuators, 4-pressure sensor, 5-temperature sensor, 6-window, 7-heaters, 8-fan, 9-weight

Source: own study

initial mass of the samples was approximately 185±0.1 g and the weight loss was measured every 60 s. The superheated steam dryer operated in a closed circuit and the maximum operating pressure was 6 atmospheres. A 21 kW steam generator produced steam, which was superheated to the set temperature by means of electric heaters. A fan provided inside the apparatus transported steam to the inside of the device. The measuring chamber was equipped with a balance, by means of which the mass of the tested sample was continuously measured during the process. The chamber was tightly closed and then, together with the sample, with the help of two actuators it was placed inside the device, in which pre-determined environmental conditions allowed direct contact of the sample with stream of flowing steam. The measurement chambers were equipped with windows through which it was possible to observe the sample during the drying process.

Investigations were carried out of flammability and explosiveness parameters of raw energy willow dust and dried dust at superheated steam temperatures at 120°C, 140°C, 160°C, 180°C in a superheated steam dryer, i.e. maximum explosion pressure – P_{max}, maximum rate of build-up of explosion pressure – $(dp/dt)_{max}$, dust explosion class, constant – K_{st}, lower explosive limit of dust clouds - MEC, minimum ignition temperature of a layer of willow dust with a thickness of 5 mm and 12.5 mm – T_{5mm}, $T_{12.5mm}$, minimum ignition energy of the willow dust cloud – *MIE*, in accordance with the test procedures described in the standards set out in Table 1.

The obtained willow dusts were then ground with a vibrating mill LMW from Testchem Sp. z o.o. (Pszów, Poland). Using a tungsten carbide bowl, an energy willow dust fraction below 200 m was obtained. A sieve analysis was then carried out on vibrating screens to separate the fine dust. For needs of the testing, dusts with grading smaller than 63 m were selected, although fractions above 63 μm may also be found in settled dusts. Such grain sizes correspond to dusts that rise during mechanical processing of grains and dusts that settle on surfaces and may pose a potential fire hazard or generate explosive atmospheres. All measurements were carried out at air temperature of 21±2°C and at atmospheric pressure of 1000 ± 5 hPa. Figures 2 and 3 show a view of the equipment used for the sieve analysis.

P_{max}, $(dP/dt)_{max}$, K_{St}, MEC [14-16] were tested using a 20 dm3 spherical chamber manufactured by Przedsiębiorstwo Produkcyjno-Usługowe ANKO Andrzej Kołaczkowski (Warsaw, Poland). The device was made of stainless steel and equipped with a vacuum pump, dust dispersion system, ignition system, pressure sensors, control system and data collection system (Figures 4 and 5).

The dust sample was placed in a vessel under air pressure. The vessel was evacuated to -0.6 bar before dispersing. The willow dust-air mixture was introduced into the apparatus through a fast acting valve and a rebound nozzle. Once the biomass dust has been introduced through the nozzle, the dust cloud was ignited by two centrally mounted chemical igniters with an energy of 5 kJ each (or by a centrally mounted single chemical igniter with a total energy of 2 kJ in the case of the LEL

Table 1. Test procedure for measuring the flammability and explosive properties of energy willow dust

Flammability and explosive properties of energy willow dust	Standard	Title
P_{max}	PN-EN 14034-1 [14]	*Determination of explosion characteristics of dust clouds - Part 1: Determination of maximum explosion pressure p_{max} of a dust cloud*
$(dP/dt)_{max}$	PN-EN 14034-2 [15]	*Determination of explosion characteristics of dust clouds - Part 2: Determination of the maximum rate of explosion pressure rise (dp/dt)max of dust clouds*
K_{st}	PN-EN 14034-2	*Determination of explosion characteristics of dust clouds - Part 2: Determination of the maximum rate of explosion pressure rise (dp/dt)max of dust clouds*
MEC	PN-EN 14034-3 [16]	*Determination of explosion characteristics of dust clouds - Part 3: Determination of the lower explosive limit LEL of dust clouds*
T_{5mm} $T_{12.5mm}$	PN-EN 50281-2-1 [17] ISO/IEC 80079-20-2 [18] PN-EN EN 50281-2-1 PN-EN ISO/IEC 80079-20-2	*Electrical apparatus for use in the presence of flammable gases - Part 2-1: Test methods - Methods for determination of the minimum ignition temperature of dust* *Explosive atmospheres - Part 20-2: Material properties - Test methods for combustible dusts* *Electrical apparatus for use in the presence of flammable gases - Part 2-1: Test methods -Methods for determination of the minimum ignition temperature of dust* *Explosive atmospheres - Part 20-2: Material properties - Test methods for combustible dusts*
T_{cl}	PN-EN 50281-2-1 PN-EN ISO/IEC 80079-20-2	*Electrical apparatus for use in the presence of flammable gases - Part 2-1: Test methods -Methods for determination of the minimum ignition temperature of dust* *Explosive atmospheres - Part 20-2: Material properties - Test methods for combustible dusts*
MIE	PN-EN 13821 [19] PN-EN ISO/IEC 80079-20-2	*Potentially explosive atmospheres - Explosion prevention and protection - Determination of minimum ignition energy of dust/air mixtures* *Explosive atmospheres - Part 20-2: Material properties - Test methods for combustible dusts*

Source: own study

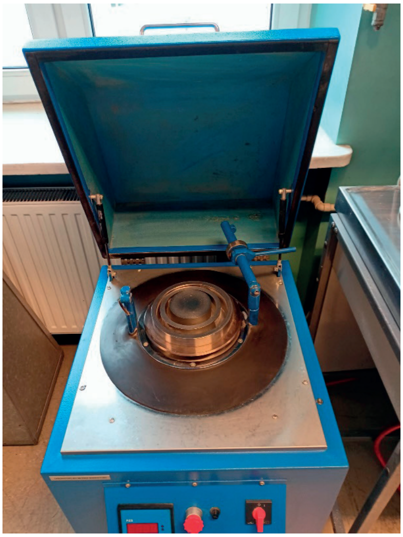


Fig. 2. View of Testchem's LMW vibrating mill

Source: own study

Fig. 3. View of vibrating sieves used for sieve analysis

Source: own study

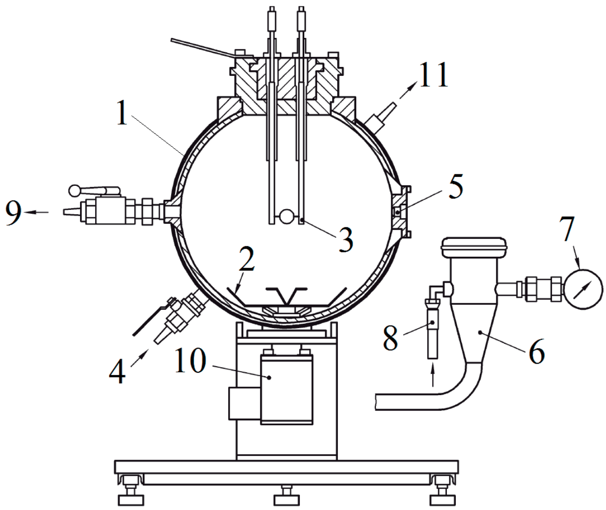


Fig. 4. Test bench scheme for determining the explosive characteristics of dust clouds, including the lower explosive limit where 1 – test tank, 2 – dispersion nozzle, 3 – ignition source, 4 – water supply, 5 – pressure sensors, 6 – dust collector, 7 – pressure gauge, 8 – air inlet, 9 – outlet, combustion products exhaust, 10 – quick acting valve, 11 – water outlet, 12 – control unit

Source: own study

Fig. 5. View of the test stand for determining the explosive characteristics of dust clouds

Source: own study

designation), following which, after a delay of 60 ms, a quasi-homogeneous dust cloud was formed, which allowed the initial turbulence to dissipate, as the blast of air with the dust to form a homogeneous cloud in the test space of the chamber with a volume of 20 dm^3 induces intense turbulence that changes significantly at the moment of ignition and explosion. A typical explosion development lasts from dozens to hundreds of milliseconds. During this time the value of the mean square pulsational velocity decreases from approx. 3.5 m/s to 1 m/s [20, 21].

As regards testing of P_{max} and $(dP/dt)_{max}$ three measurement series were executed, varying the concentration of willow dust in the range of 250 g/m^3, 500 g/m^3, 750 g/m^3, 1000 g/m^3, 1250 g/m^3 and 1500 g/m^3. The arithmetic mean of the three results P_{max} and $(dP/dt)_{max}$ was taken as the test result obtained in each of the three series carried out. For the determination of *MEC*, three series of measurements were carried out, starting with the concentration of 500 g/m^3, and then 250 g/m^3, 125 g/m^3 and 60 g/m^3.

The minimum ignition energy of the energy willow dust cloud was established in a Hartmann apparatus (MINOR 2, manufactured by ANKO, Warsaw, Poland) [18, 19]. The device consisted of a vertical glass tube with a volume of 1.2 dm^3 and a length of 70 cm together with a pneumatic dust dispersal system with an overpressure of up to 7 bar and a spark generation circuit [22]. The view of the test stand is shown in Figure 6.

Fig. 6. View of the test rig for determining the minimum ignition energy of air-dust mixtures

Source: own study

The control panel of the device made it possible to set the delay time from 0 ms to 10000 ms (±10 ms) and to adjust the energy of the discharge spark to the values of 1 mJ, 3 mJ, 10 mJ, 30 mJ, 100 mJ, 300 mJ, and 1000 mJ. According to PN-EN 13821 [19], ignition was the spread of a self-sustaining flame from the point of a spark discharge. The minimum ignition energy of an explosive dust-air mixture of energy willow was the lowest value of electrical energy stored in a capacitor which, when discharged, is sufficient to ignite the most ignitable mixture of a given dust under the specified test conditions. Considering the provisions of the standard EN 13821, the following concentrations of willow dust were tested: 125 g/m^3, 250 g/m^3, 500 g/m^3, 750 g/m^3, 1000 g/m^3, 1250 g/m^3, 1500 g/m^3, 1750 g/m^3, 2000 g/m^3, 2500 g/m^3 and 3000 g/m^3 with a spark gap inductance of 1 mH and 1 µH. The testing was started with a spark discharge energy of 1000 mJ. The ignition was assessed visually by the tester. The minimum ignition energy was determined between the highest energy at which the air/dust mixture did not ignite in 10 consecutive tests and the lowest energy at which ignition occurred in one of 10 consecutive tests.

The minimum ignition temperature of the 5 mm and 12.5 mm thick energy willow dust layer has also been evaluated [17, 18, 23], using the test stand LIT-3, built by ANKO, Warsaw, Poland (Figure 7).

Fig. 7. View of test bench for determining the minimum ignition temperature of the dust layer, where 1 – posts for mounting, tensioning and adjusting the height of position of measuring thermocouple, 2 – heating plate temperature regulator, 3 – ring with sample of tested dust, 4 – furnace body, 5 – control thermocouple, 6 – computer temperature recorder, 7 – measuring thermocouple, 8 – heating plate

Source: own study

A Godbert-Greenwald vertical furnace (MAIT/MIT, Anko, Poland) [17, 18, 23], constructed of a silica tube, 3.9 cm in diameter and 23 cm high, was used to determine the minimum ignition temperature of the dust cloud. This tube was heated to the desired temperature using a device that controls temperature of the furnace. A stainless steel mirror was located underneath the tube to allow visual monitoring of the furnace interior. Figure 8 shows a view of the test rig for determining the minimum ignition temperature of the dust cloud.

Fig. 8. View of the test rig for determining the minimum ignition temperature of a dust cloud – Godbert-Greenwald furnace

Source: own study

3. Results and discussion

The effect of superheated steam drying temperature on the fire and explosion parameters of the energy willow dust-air mixtures was investigated experimentally (120°C, 140°C, 160°C, 180°C). The results obtained for the flammability and explosiveness parameters of the analysed energy willow dusts before and after the drying process are presented in Table 2.

Energy willow dust is classified as low explosive (St 1). It should be noted that the dust obtained after drying with superheated steam at a temperature of 180°C is characterised by the highest value of the parameter K_{st} equalling to 37±14m·bar·s^{-1} which means that the explosion velocity reaches 5 m/s, indicating a slow combustion of the dust-air mixture. It is also characterised by the highest rate of explosion pressure build-up (138 ±4 bar/s), which can cause the most damage during a possible incident at a biomass overheated steam drying installation, particularly indoors. The value of the constant $K_{st\ max}$ was recorded at a concentration lower than the dust concentration at which the maximum explosion pressure was estimated (Figure 9).

MEC studies have shown that the lowest concentration value for which willow dust generated before the superheated steam drying process can create an explo-

Tab. 2. Comparison of ignitability and explosiveness parameters for fresh and dried energy willow dust at temperatures of 120°C, 140°C, 160°C and 180°C

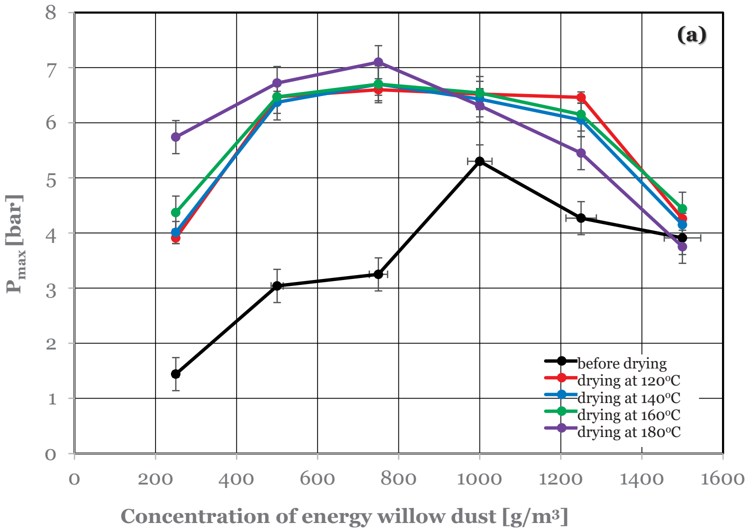
Designated parameter	**Before the drying process**	**After the drying process at**			
		120°C	**140°C**	**160°C**	**180°C**
Contents of humidity in samples, %	44.4	2.6	1,9	1,3	0,5
P_{max}, bar	5.3±0.3	6.6±0.3	6.7±0.3	6.7±0.3	7.1±0.3
$(dP/dt)_{max}$, bar/s	54±16	109±34	114±33	120±36	138±4
K_{st}, (m·bar)/s	15±4	30±5	31±11	33±9	37±14
MEC, g/m^3	250±20.1	125±11.2	125±9.7	125±9.3	125±9.1
MIT_{5mm}, °C $MIT_{12.5mm}$, °C	320±2.9 298±2.7	300±2.8 286±2.6	290±3.0 280±2.8	290±2.8 279±2.9	290±2.9 280±2.8
T_{cl}, °C	440±2.8	480±3.6	490±3.6	500±3.6	520±3.6
MIE, mJ	300<MIE<1000	100<MIE<300			

Source: own study

sive atmosphere is 250 g/m^3. MEC values of dust after the drying process at temperatures of 120°C, 140°C, 160°C, 180°C are lower and already at a concentration of 125 g/m^3 dust is in the explosive range. This value is very close to the results obtained for spelt hulls, nut shells, pine cones and straw and indicates the possibility of ignition of dust-air mixtures at relatively low dust concentrations.

The moisture content of willow dust and hence the parameters of the superheated steam drying process have a major influence on the dust explosion characteristics. As can be seen from Table 2, for willow dust with increased moisture content, P_{max} and K_{st} decrease. This is caused by dust agglomeration, the effect of the superheater, steam inertisation or the reduction of mass transfer at the particle surface, i.e. they result from heat loss for water evaporation.

The value of minimum ignition energy *MIE* of the energy willow dust cloud is needed to assess the risk of superheated steam drying installations. Results shown in Table 2 indicate that the minimum ignition energy increases with increasing moisture content of the material. It appears that willow dust after the superheated steam drying process is susceptible to ignition from initials below 300 mJ. The determined value of MIE, in laboratory conditions, may be lower in actual process conditions, as in the drying process there is an increased air temperature. Energy willow dust clouds can be ignited by electrical sparks and arcs occurring in switches and motors and in the event of a short circuit caused by faulty electrical wiring. It is therefore important to eliminate or reduce potential ignition sources (e.g. by electrostatic earthing) with particular attention to procedures meant to control ignition sources.



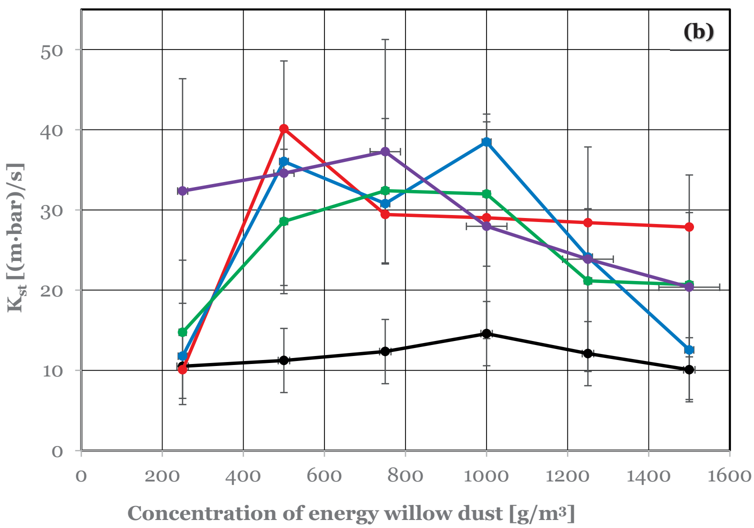


Fig. 9. Effect of willow dust concentration on (a) P_{max} and (b) K_{st}

Source: own study

The temperature of the biomass drying process with superheated steam and the moisture content of the material will influence the susceptibility of the dust to ignition and the dynamic combustion propagation throughout the volume of the dust-air cloud. After the process of drying with superheated steam at the temperature of 180°C energy willow biomass dust has a higher value of the minimum cloud ignition temperature by 80°C as compared with the dust which can be formed during the processing of raw energy willow. This is due to a higher moisture content in the material and a reduction in dust dispersion by increasing intermolecular cohesion.

However, the effect of the superheated steam drying temperature of the biomass on the ignition temperature of the willow dust layer in contact with the surface is not so pronounced. For example, the value of the minimum ignition temperature of dry biomass with a moisture content of 0.5% tested was MIT_{5mm} 290°C ±2.93 while for willow having a humidity of 44.4% MIT_{5mm} it was 320°C ±2.9. Furthermore, the results have shown that the minimum ignition temperature increases with increasing moisture content in the biomass. When analysing the minimum ignition temperature, it should be noted that MIT depends on the thickness of the deposited dust layer. Whenever this temperature was measured for a 12.5 mm layer, the MIT was on average 20-30°C lower than that for a 5 mm thick dust layer. Another important factor is the ignition time, which also depends on the thickness of the dust layer. A thicker dust layer reduces MIT and also increases the ignition time in the layer. The maximum temperature for the equipment of a superheated steam drying system covered with a layer of energy willow dust up to 5 mm thick should not exceed 75°C of the following minimum ignition temperature of the dust layer, in this case it is 215°C.

In order to eliminate fire and explosion hazards to facilities and equipment in the area of superheated steam drying installations, it is necessary to prevent the spread of dusts outside the installations, and in the case of emergency incidents to remove them systematically from the external surfaces of machines and equipment. It is crucial to regularly remove biomass dust from floors, walls and stairs using Ex vacuum cleaners that meet ATEX requirements for dust explosive zones.

4. Summary

The conducted studies have shown that the operating parameters of a superheated steam drying installation for energy willow biomass clearly influence the fire and explosion characteristics of the resulting willow dust. The obtained results indicate that the lower the moisture content of the willow, the more likely the dust cloud is to ignite, the faster the explosive flame will spread and the greater the intensity of the explosion phenomenon. Although the superheated steam drying installation is considered safe due to the absence of oxygen in the dryer, the probability of occurrence of fire or explosion events of the energy willow biomass dust-air mixture is likely within the industrial drying installation as a result of e.g. failure of the heating and ventilation unit (fan friction, short-circuit in the motor) or damage, short-circuit, overload of the electrical installation located in the drying chamber [24–29].

The maximum temperature for equipment in a superheated steam drying system covered with a layer of energy willow dust up to 5 mm thick may not exceed 75°C below the minimum ignition temperature of the dust layer, in this case 215°C according to the standard method [30–32].

On the basis of experimentally determined drying characteristics of wet bark, optimal drying at 13% wt. water content was assessed. It can also be concluded that drying above 31% wt. water content in the bark is quite unfavourable due to the fact that at this stage the drying efficiency continues to increase rapidly and the required relative dryer size decreases.

On the basis of experimental results and past experience [33–35], the adoption of general fire prevention measures is recommended, i.e. the process should be conducted in such a way that the premises are dust-free. In order to limit dust accumulation inside the premises, a cleaning plan should be implemented at regular intervals, wet cleaning of the equipment or using EX-compliant vacuum cleaners for dust explosive areas should be carried out to avoid dust. Effective systems of equipment maintenance should be implemented, staff should be regularly trained in safety rules and fire regulations, regulations for work hazardous to fire, i.e. at elevated temperatures, should be observed and permits should be obtained for this type of work.

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