

Artificial Sweeteners or High Risk Sugar Alcohols

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ABSTRACT

Growing popularity of artificial sweeteners commonly used as a sucrose substitute causes a rapid increase in their production which is close to 2 million metric tons annual. Large quantities both produces, transported and stored organic materials naturally pose a threat of a major industrial accident which can be prove only by a series of breakdowns related to the explosion of sugar dust. The purpose of this work was to determine and compare parameters describing thermal stability and characteristics of burning process of six compounds of the sugar alcohols: xylitol, D-mannitol, D-sorbitol, maltitol, myo-inositol, meso-erythritol; with sucrose. We also investigated gaseous products generated during thermal decomposition of tested polyalcohols. The tests were conducted using following devices: cone calorimeter, smoke density chamber, purser furnace, differential scanning calorimeter, gas chromatography in accordance with appropriate standards. Almost all of tested sugar alcohols generate more heat during combustion than sucrose. Under higher values of applied heat flux, maltitol shows the highest maximum heat release rate although its ignition time is almost twice the time of sucrose. The only compound that did not ignite during smoke density measurements was meso-erythritol. Sucrose did ignite before the VOF4 parameter could be measured. Based on gained results it can be concluded that under specific conditions sugar alcohols can be equally or even more dangerous than sucrose.

KEYWORDS: sucrose, sugar alcohols, cone calorimeter, smoke density chamber, heat release rate

INTRODUCTION

Sucrose is the most popular disaccharide used as a sweetener in food industry. It's annual global production ranks at 170 million metric tons [1]. Such large production quantity of organic compound in natural way poses a threat of the possibility of a major industrial accident. Chemical Safety Board in the report on fires and explosions of sugar dust stated that first reported combustion of sugar dust took place in 1925. Almost 100 years later, despite broad knowledge and security measures, accidents still occur i.e. sugar dust explosion; silo tower (Cantley, England, 2003), sugar mill (Baltimore, USA, 2007), silo tunnel (Georgia, USA, 2008); sugar fire: sugar warehouse (Santos, Brazil, 2013). [2, 3].

In the meantime group of artificial sweeteners appeared on the market. Those new and often unexamined in case of fire scenarios compounds from the group of sugar alcohols (polyols) may have similar or even stronger fire and explosion characteristics than sucrose. According to literature [4] global annual production scale of sugar alcohols i.e. sorbitol, xylitol, mannitol, maltitol and isomalt is 1.6 million metric tons and increases rapidly. It is assumed that it will reach value of 2 million metric tons by the end of year 2022. Such large production scale of organic compounds, despite the current lack of incidents reports, poses a threat of a major industrial accident. Sugar alcohols dust qualifies as a potentially flammable or explosive due to their chemical structure. Short carbon chains combined with several hydroxyl groups significantly increases molecular oxygen

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balance in those compounds which makes them good fuel even in low oxygen conditions. Due to those properties sugar alcohols found application in pyrotechnics and explosives. Combined with nitrating mixture polyols form unstable and very strong explosive materials i.e. pentaerythritol tetranitrate (PETN) also known as penthrite, one of the most powerful modern secondary explosive, which is a derivative of pentaerythritol, polyol commonly used as an artificial sweetener [5]. Based on those information we decided that there is an urgent need to conduct studies of compounds so widely used and processed in large quantities for their flammability and explosive properties.

In this study we focused on the recognition of parameters describing the combustion process of six sugar alcohols: xylitol, D-mannitol, D-sorbitol, maltitol, myo-inositol, meso-erythritol and compared them to the values obtained for sucrose. Fire parameters were measured using two devices: cone calorimeter and smoke density chamber, in accordance with standards: ISO 5659 and ISO 5660. The thermal stability of selected materials was evaluated by thermogravimetric analysis (TG). Moreover, the steady state tube furnace (Purser furnace) has been used specifically to generate toxic products from real fires. The released species have been identified using gas chromatography with mass selective detector (GC-MS).

MATERIALS AND METHODS

Materials

All tested sugar alcohols are commercially available products delivered by Acros Organics and Alfa Aesar. The purity of tested compounds was 98-99%, except for Maltitol which purity was 95%. To create more comparable conditions all compounds were minced by a grinding mill and gained powder was subjected to a sieve analysis. Materials of equal grain size range (75-125 μm) were further used to determine calorimetric parameters.

Cone calorimeter flammability testing

Fire safety characteristics require the determination of the basic behavioral parameters under fire conditions. Parameters characterizing behavior of analyzed compounds in the presence of flame were studied using Dual Cone Calorimeter (FTT Limited, West Sussex) according to standard ISO 5660-1 [6]. Three samples of equal mass (20 grams) for each compound, were covered with aluminum foil (100 mm x 100 mm x 25 mm) and treated with external Heat Flux (HF) in range of 25-75 kW/m^2 simulating the thermal exposure during the first phase of fire. Based on gained results following parameters were estimated: Heat Release Rate – *HRR* (kW/m^2), peak of Heat Release Rate – *pHRR* (kW/m^2) time to peak of Heat Release Rate – *t-pHRR* (s), Total Heat Release – *THR* (MJ/m^2), Ignition Time – *TTI* (s), Total Smoke Release – *TSR* (m^2), Fire Growth Rate – *FIGRA* ($\text{kW/m}^2\text{s}$), Thermal Response Parameter – *TRP* ($\text{kW}\cdot\text{s}^{1/2}/\text{m}^2$).

NBS smoke density testing

The smoke density characteristics in a closed room can be described by two main parameters: Optical Density of Smoke (*D_s*) and *VOF4*. *D_s* parameter determines visibility reduction and is the determinant of an amount of smoke produced during the first ten minutes of thermal degradation of tested material. *VOF4* describes increasing rate of smoke density during the first four minutes, which are crucial during evacuation process. *VOF4* parameter is calculated according to the Eq. (1):

$$VOF4 = \frac{1}{2}(1D_{s1} + 2D_{s2} + 2D_{s3} + D_{s4}), \quad (1)$$

where *D_{s1}*, *D_{s2}*, *D_{s3}*, *D_{s4}* – optical densities of smoke during four consecutive minutes of the test.

All parameters were measured using Smoke Density Chamber (FTT Limited, West Sussex) according to standard ISO 5659-2 [7]. Three samples of equal mass for each tested compound, were

covered with aluminum foil (75 mm x 75 mm x 10 mm) and treated with external HF of 25 kW/m². Due to the high flammability of the test compounds, even in the absence of the ignition source (electric spark), two relevant comparative parameters were added: Time to Maximum Smoke Density (*TMDS*) and Ignition Time (*TTI*).

Thermal analysis

The thermal degradation characteristics of polyalcohols were analyzed by the methods of TG-DTG and DSC using a simultaneous thermal analyzer (STA 449F3 Jupiter, Netzsch, Germany). The mass of the investigated materials was 10 mg. The heating rate was 10 K/min. The measurements were carried out in the air and nitrogen atmosphere.

Fire effluent analysis

Samples of materials (15 g) in test boats were delivered into the steady state tube furnace (ISO 19700) set at 350°C. The collection of fire effluent from mixing chamber of tube furnace was performed with the use of the solid phase microextraction manual holder supplied with carboxen/polydimethylsiloxane 75 μm fiber acquired from Supelco (USA). The sorption and desorption time was 5 min and 30 min accordingly. The chromatographic separation was achieved with an HP-5 MS fused silica capillary column (30mm×250μm×0.25μm film thickness) from Agilent Technologies (USA). The oven temperature was initially maintained at 40°C for 5 min, and then increased to 250 °C at the heating rate of 4 °C/min. Helium at the constant flow rate of 1 ml/min was used as the carrier gas and the split ratio was 10:1. The separated compounds were then analyzed by the mass spectrometer, which was operated in electron ionization (70 eV). The mass spectra were obtained from m/z 15 to 350. Chromatographic peaks were identified with NIST MS Library.

RESULTS AND DISCUSSION

Cone calorimeter parameters

The thermal response parameter (TRP) allows to estimate material resistance to generation of combustible gas mixture [8, 9]. The higher the TRP value, the longer it takes for the material to heat up, evaporate, ignite, and initiate a fire. TRP depends on the series of parameters ignition temperature (T_{ig}), ambient temperature (T_{∞}), thermal conductivity (λ), specific heat (C_p) and density (ρ) and can be calculated according to the Eqs. (2) and (3):

$$TRP = (T_{ig} - T_{\infty}) \sqrt{(\pi/4) \lambda \rho C_p} , \quad (2)$$

$$t_{ig} = (\pi/4) \lambda \rho C_p \left((T_{ig} - T_{\infty}) / q_e'' \right)^2 \quad (3)$$

By the combination of Eq. (2) with Eq. (3), *TRP* can be presented as a function of external heat flux, q_e'' , and t_{ig} :

$$t_{ig}^{-1/2} = q_e'' / TRP \quad (4)$$

The plot of the square root of the ignition time inverse versus the external heat flux allows to interpret the *TRP* from the curve slopes according by Eq. (5):

$$TRP = 1 / slope . \quad (5)$$

All TRP values are presented in Table 1. Average values of parameters characterizing the behavior of sugar alcohols under the influence of intense radiant heat gained during cone calorimeter measurements were summarized in Table 2.

Table 1. TRP values calculated for tested sugar alcohols

Sample	TRP
	$\text{kW}\cdot\text{s}^{1/2}/\text{m}^2$
D-mannitol	500
D-sorbitol	476
xylitol	500
maltitol	476
meso-erythritol	526
myo-inositol	400
sucrose	270

Sucrose

Based on the gained results it can be concluded that in a range of lower HF (25-50 kW/m^2) sucrose gain the highest values of *pHRR* and second only to maltitol at 75 kW/m^2 . The *HRR* curves presented in Fig. 1, suggest that sucrose does not reach its fully grown steady flaming phase under any HF. Twenty gram samples simply burn to fast to reach maximum potential of this compound even under such low HF as 25 kW/m^2 .

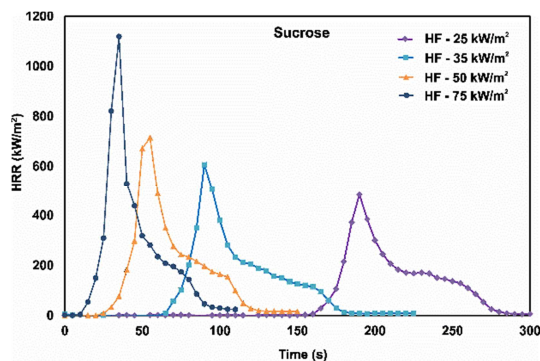


Fig. 1. HRR development for sucrose under different HF.

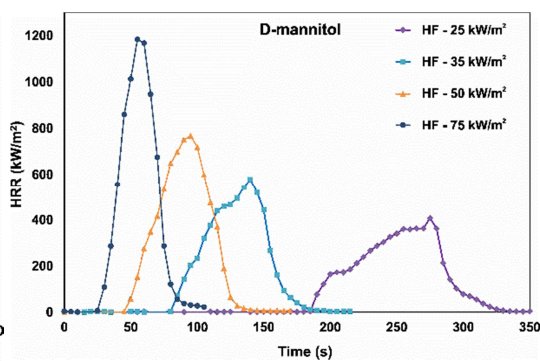


Fig. 2. Comparison of maltitol HRR development under different HF.

After the first peak one can observe (especially at 25 and 35 kW/m^2), the flaming phase with *HRR* at the level of 200 kW/m^2 , but it is mostly due to the decomposition of weak char created during pyrolysis and the lack of pure organic material. Although sucrose is one of the largest tested compounds (only 2g/mol lighter than maltitol), it reaches lowest *THR* values. Probable explanation of this behaviour is associated with the chemical structure and chemical reactions in condensed phase. When heated above 140°C sucrose starts to decompose (caramelize) generating furans (i.e. furfuryl alcohol) with very low flashpoint temperature (*Fp*) (60-80°C) which is also the cause of short *TTI* under higher *HF* and in consequence very low *TRP* [10].

Table 2. Calorimetric values of fire parameters for sugar alcohols and sucrose

Sample	<i>TTI</i>	<i>FIGRA</i>	<i>HRR</i>	<i>pHRR</i>	<i>t-pHRR</i>	<i>THR</i>	<i>TSR</i>
	s	kW/m ² s	kW/m ²	kW/m ²	s	MJ/m ²	m ² /m ²
HF – 25 kW/m ²							
D-mannitol	224	0.87	170	256	293	31.9	43.8
D-sorbitol	197	0.88	152	228	260	31.7	42.1
xylitol	144	0.96	130	232	242	33.6	52.6
maltitol	209	1.51	196	415	285	29.0	60.7
meso-erythritol	110	1.25	164	247	197	31.7	35.6
myo-inositol	116	1.77	139	228	128	28.4	37.8
sucrose	165	2.59	150	484	187	20.7	5.22
HF – 35 kW/m ²							
D-mannitol	108	2.33	183	362	155	31.7	72.9
D-sorbitol	104	2.22	170	344	155	31.3	72.9
xylitol	77	2.26	138	301	133	31.5	79.5
maltitol	88	3.9	237	580	148	29.8	98.7
meso-erythritol	72	2.7	185	371	138	32.1	63.1
myo-inositol	60	4.46	126	305	68	28.0	65.1
sucrose	70	6.57	161	614	93	22.4	61.5
HF – 50 kW/m ²							
D-mannitol	65	4.46	263	491	110	34.9	207
D-sorbitol	63	6.32	241	558	88	35.2	206
xylitol	56	4.30	224	466	108	36.0	214
maltitol	65	7.78	297	764	98	35.5	219
meso-erythritol	48	4.50	262	472	105	36.6	202
myo-inositol	36	10.4	231	467	45	32.6	165
sucrose	29	14.0	197	771	55	23.8	47.2
HF – 75 kW/m ²							
D-mannitol	34	14.0	281	840	60	33.1	105
D-sorbitol	33	10.7	346	787	73	34.7	183
xylitol	29	8.03	272	616	77	34.1	162
maltitol	31	20.2	503	1144	57	36.2	230
meso-erythritol	29	7.88	300	578	73	35.7	211
myo-inositol	24	20.4	281	647	32	32.9	184
sucrose	17	29.8	250	1119	35	25.7	50.7

Maltitol

Main difference between maltitol and sucrose is the presence of the oxolane (tetrahydrofuran) ring instead of d-glucitol chain, so the combination of two cyclic ethers can explain reduction of molecule energy and t_{ig} . Secondly, maltitol does not undergo caramelization process and because cone calorimeter parameters are based on oxygen level in flaming phase, it is possible that

decomposition of sucrose in the condensed phase is responsible for its low *THR*. As a result of analysis of maltitol's *HRR* curve under the $HF = 25 \text{ kW/m}^2$, it can be concluded that the initial increase of the *HRR* is being followed by a slow growth up to the maximum value, see Fig. 2.

The initial raise is related to the ignition of flammable pyrolysis products whose concentration in the gas phase was sufficient to initiate a self-sustaining combustion process while the second stage is limited by the rate of decomposition and the emission of combustible products into the combustion zone. Similar behaviour can be observed under the $HF = 35 \text{ kW/m}^2$, but in that case time of the growing phase is much shorter and the angle is higher. This characteristic changes under the influence of heat source in temperature range $750\text{-}900^\circ\text{C}$ ($HF = 50\text{-}75 \text{ kW/m}^2$). In both cases it is hard to separate ignition phase from the growing phase. Decomposition process is fast enough, to provide sufficient amount of flammable gaseous to the flaming zone, to keep the stable growth of *HRR*. Due to the high molecular weight and contribution of functional groups, maltitol shows the highest *HRR*, *THR* and *TSR* values. Maltitol, like the other sugar alcohols, does not caramelize, therefore vaporized macromolecules generates large amount of soot in burning phase as a result of incomplete combustion.

D-sorbitol and D-mannitol

Two of tested sugar alcohols: d-mannitol and d-sorbitol, shows good thermal stability in low range of *HF*, without reaching characteristic *HRR* peak. Development of burning process in both cases leads to a maximum *HRR* after 2,5-3 minutes after the ignition and last until most of the organic material has been burned, see Fig. 3.

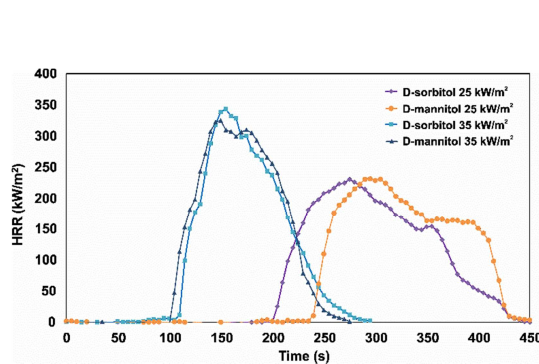


Fig. 3. D-sorbitol and d-mannitol *HRR* curved under $HF = 25,35 \text{ kW/m}^2$.

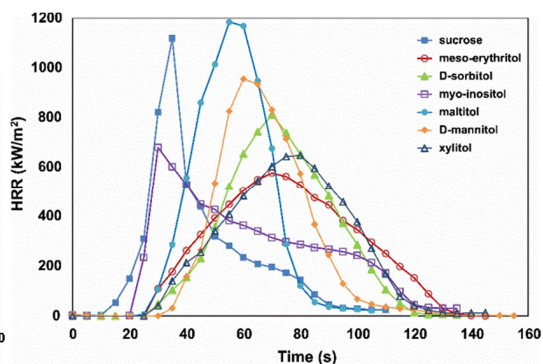


Fig. 4. Comparison of *HRR* development during burning stage for tested compounds ($HF = 75 \text{ kW/m}^2$).

Similar characteristic of burning process of those two compounds is related to their identical chemical composition. Both compounds are isomers, and differ only in spatial orientation of hydroxyl group at second carbon atom. Even such subtle structural difference has an impact on compounds behaviour under fire conditions. As can be seen from the Table 1 data, D-mannitol is characterized by higher thermal stability (longer t_{ig}) than D-sorbitol.

Myo-inositol

Myo-inositol is one of the most interesting tested sugar alcohols. It is characterized by short t_{ig} and relatively high FIGRA values. On the other hand myo-inositol shows low *HRR*, and its flaming phase is statistically longer then for the rest of the tested compounds (Fig. 4.). Such characteristic is typical for compounds with the ability to generate a layer of swollen char on the surface of the sample under pyrolysis conditions. Similar phenomenon can be observed in plastics with an

addition of intumescent flame retardants, where specific additives are responsible for generation and swelling process of formed char that protects polymer against the influence of external heat and oxygen [11,12]. Probable reason for the char formation is the presence of cyclohexane ring. Dehydration of hydroxyl groups leads to the formation of double bonds and aromatic structures being the foundation of char. It's worth noticing that rapid development of burning process and short TTI are important parameters for the evaluation of combustion characteristics of dust-air mixtures.

In such conditions myo-inositol will not be able to generate the char layer and will burn with the highest possible rate which can lead to very high explosion characteristics, similar or even stronger than sucrose. This lead will be further investigated and described in another paper.

Meso-erythritol and xylitol

Erythritol like the most of sugar alcohols does not have aldehyde or ether groups, therefore it does not undergo a Maillard reaction or caramelization and is relatively stable to heat ($F_p = 209^\circ$). This means that erythritol rather vaporize than decompose during first stage of fire and its F_p is much higher than F_p of sucrose's decomposition products, like furfuryl alcohol (77°C) [13,14]. It was observed that compounds without structural rings show higher TRP values. For example, TRP of meso-erythritol is much higher than of any other tested sugar alcohol while sucrose, compound with two structural rings, shows the lowest TRP value. Although TRP is not the most accurate parameter, it allows defining general rules of behavior. Meso-erythritol is characterized by short TTI at $HF = 25 \text{ kW/m}^2$, but increase of HF to 75 kW/m^2 does not cause such drastic change in t_{ig} as in case of sucrose or maltitol and is a reason for smaller experimental line slope. This deduction coincides with the results gained from the smoke density chamber. For typical sugar alcohol, $pHRR$ value doubles with the change of HF from 35 to 75 kW/m^2 and for meso-erythritol it rises by about 56% see Fig. 5.

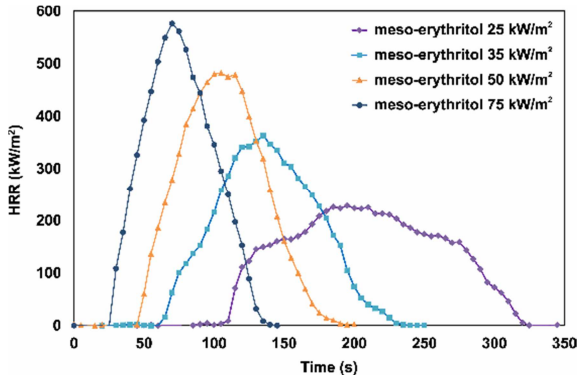


Fig. 5. Meso-erythritol HRR curves under different HF.

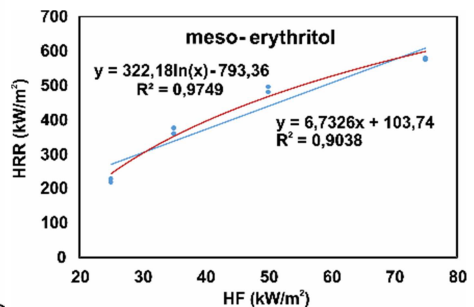


Fig. 6. Meso-erythritol's $pHRR$ dependency on HF value.

Probably meso-erythritol is much closer to its maximum combustion rate and in this range HRR ceases to be linearly dependent on the power of the heat source and changes to a logarithmic dependency, see Fig. 6.

Xylitol is a compound most similar to the meso-erythritol based on the chemical structure. Additional carbon atom and hydroxyl group does not make significant changes in calorimetric parameters although show noticeable impact on smoke density and TTI during smoke chamber tests.

Smoke density chamber parameters

The results gained from the smoke density chamber tests indicate that the meso-erythritol, compound with the shortest *TTI* during cone calorimeter test, under same heat flux (25 kW/m²), was the only one that did not ignite, see Table 3. This can be explained by the small mass of meso-erythritol. Four-hydroxyl butanoic chain probably evaporates from the sample before reaching the decomposition temperature, which is high enough to keep it from ignition in contact with a heat source of about 600°C without the presence of an electric spark.

Longest *TTI'* was observed for xylitol, compound most similar to meso-erythritol, than for isomers: d-mannitol and d-mannitol, maltitol and sucrose. Those results strongly agree with the conclusions drawn from the analysis of *TRP* values. Myo-inositol, due to its ability to form swollen char layer, did not ignite during the first test, resulting in a *VOF4* value of 204. Unfortunately, formed char is not always dense enough to effectively protect the sample from external heat, especially in case of compound with such a short tig and high *FIGRA* values like myo-inositol which ended in very short tig' during second test. Sucrose tig' was too short to determine *VOF4* parameter. Maximum value of smoke density obtained after ignition cannot be a comparative criterion for individual substances since the presence of a flame source interferes with the readings of the analyzer, making it impossible to determine the actual degree of smoke inside the chamber, hence further comparability of smoke density is unfounded. Lowest *VOF4* parameter was recorded for D-sorbitol with a self-ignition temperature of 420°C [15]. This compound ignited 6-7 minutes after the test began, allowing estimation of *VOF4* parameter on the level of 48,3. In turn, the highest value was obtained for mesoerythritol.

Table 3. Summary of smoke density chamber parameters for tested compounds

Sample	<i>D_s</i> (<i>TMDS</i>)	<i>VOF4</i>	<i>TTI'</i>
	- (s)	-	s
D-mannitol	497 (418)	51.6	410
D-sorbitol	391 (395)	48.3	395
xylitol	673 (433)	109	452
maltitol	281 (256)	148	251
meso-erythritol	890	238	-
myo-inositol	147 (530) / 507	- / 204	131 / -
sucrose	175 (202)	-	143

Table 4. Thermogravimetric characteristics of the selected polyalcohols

Chemical	Atmosphere	Mass losses (%)	Melting point (°C)	Beginning of degradation process (°C)	End of degradation process (°C)
D-Mannitol	Air	99.98	166	345.9	390.4
	Nitrogen	99.73	167.6	334.6	393.7
D-Sorbitol	Air	100	99.8	346.4	396.1
	Nitrogen	100	99.9	341	395.2
Xylitol	Air	99.75	94.2	309	368.1
	Nitrogen	100	95.2	309	367.3

Maltitol	Air	99.36	149.6	293	593
	Nitrogen	94.16	149	280	406
Meso-Erythritol	Air	100	119.6	268.9	323.9
	Nitrogen	99.86	120.8	277.9	352.4
Myo-Inositol	Air	99.69	-	148	586.4
	Nitrogen	93.19	-	148.9	394.8
Sucrose	Air	100	189.7	225.6	634.8
	Nitrogen	81.08	191.8	227.7	456.1

Thermal degradation studies

The TG, TDG and DSC curves for polyalcohols showed that thermal degradation in air atmosphere for all tested substances except meso-erythritol occurred in multi stage. When the testes were carried out in the nitrogen atmosphere, all substances except myo-inositol undergo one-stage degradation. The mass losses depended on the gaseous atmosphere used during the test and type of polyalcohol (Table 4).

The lowest temperature of the beginning of degradation process was observed for myo-inositol. That chemical was of xylitol in the air atmosphere, the sudden increase in temperature was observed, which may suggest that the tested substance ignited during the measurement. This phenomenon additionally decomposed in a complex way in both studied atmospheres. Interestingly, during the thermal decomposition of xylitol carrying out in nitrogen that situation was not observed.

Fire toxicity

The type of products formed during the measurements depends on the composition of the test material. However, some products such as ethenyl ester formic acid and hydroxy-acetaldehyde were presented in all gaseous samples. The largest number of thermal degradation products were created during the decomposition of the maltitol, myo-inositol and sucrose. Following chemicals were identified in samples of emitted gasses during the thermal degradation of those materials: furfural, 3-furaldehyde, 2-acetylfuran, 5-methyl-2-furancarboxaldehyde and furyl hydroxymethyl ketone. During thermal degradation of hydrogenated monosaccharides (d-mannitol, d-sorbitol and xylitol) in fire effluents furfural was also presented. All these substances are present in many food items as the natural products or as the contaminants. For example 2-acetylfuran is found in alcoholic beverages. 2-Acetylfuran as well as furfural, 3-furaldehyde, 5-methyl-2(5H)-furanone, 5-methyl-2-furancarboxaldehyde are used in flavored products. The 5-methyl-2-furancarboxaldehyde is a secondary produced from saccharides. Therefore, it can be assumed that the presence of these products in the emitted gas mixture can be caused both by the thermal degradation of polyalcohols and their presence in the tested materials. Table 5 presents the concentrations of released compounds during thermal degradation of selected materials using Purser furnace.

CONCLUSION

The characteristic parameters for the thermal decomposition during fire of sugar alcohols were quantitatively investigated with the use of cone calorimeter under a series of *HF* settings and smoke density chamber. Correlation analysis between the *HF* and the characteristic parameters was performed and properly described. Based on gained results in can be concluded that sucrose is the most flammable compound with most rapid fire growth, especially under higher *HF*. Yet it is important to notice that almost all tested sugar alcohols show higher average *HRR* and *THR* value, three of which under lower *HF* shows shorter *TTI*. Under the influence of 75 kW/m² *HF*, maltitol's *pHRR* was noticeable higher than sucrose's wherein the other parameters where significantly higher.

Myo-inositol shows very short t_{ig} and high *FIGRA*, but the fire growth is being inhibited by char layer forming on the surface of the sample. The thermal degradation characteristics of polyalcohols were analyzed by the methods of TG-DTG and DSC, and the results showed that most of the tested materials were decomposed as a result of a multi-stage process. In samples of gases and fumes, emitted during the thermal degradation and combustion of polyalkohols many chemicals were identified. The detected decomposition products depended on the type of substance that was degraded.

Table 5. Products formed during thermal degradation and combustion of tested polyalcohols

Compound	Emission yields (peak area x 10 ⁶)						
	D-Mannitol	D-Sorbitol	Xylitol	Meso-Erythritol	Maltitol	Myo-Inositol	Sucrose
CO. CO ₂	78.7	97.0	102.4	98.2	84.7	80.5	127.1
Formic acid. ethenyl ester	18.4	34.0	41.7	28.6	34.3	20.5	41.9
Acetaldehyde. hydroxy-2(5H)-Furanone. 5-methyl-	4.12	7.74	14.4	13.8	10.3	6.87	26.0
Furfural	3.46	14.8	33.4	-	64.40	62.15	300.1
2-Furanmethanol	-	1.72	27.7	-	-	-	-
3-Furaldehyde	-	-	-	-	22.05	11.9	12.2
2-acetylfuran	7.17	9.60	-	-	25.0	12.4	14.6
2-Cyclopenten-1-one. 2-hydroxy-	-	-	-	-	7.34	8.12	21.7
2(5H)-Furanone. 5-methyl-	-	-	-	-	39.3	15.3	13.5
2-Furancarboxaldehyde. 5-methyl-	-	-	-	-	15.0	25.9	140.3
Phenol	-	-	-	-	6.66	18.16	7.03
Hydroquinon	6.59	7.23	-	-	28.9	2.16	3.87
2-Cyclopenten-1-one. 2-hydroxy-3-methyl-	6.63	1.01	-	-	20.1	5.69	17.5
3,4-Furandiol. tetrahydro-. trans-	-	-	201.8	196.0	-	-	9.68
2,5-Furandicarboxaldehyde	-	2.84	-	-	-	2.00	54.6
Furyl hydroxymethyl ketone	2.41	-	-	-	22.9	41.8	106.8
5-Acetoxyethyl-2-furaldehyde	-	-	-	-	-	-	65.7
5-Methyl-2-(5-methyl-2-furfuryl)furan	-	-	-	-	9.74	3.26	65.2
5-Hydroxymethylfurfural	-	-	-	-	-	-	138.0

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