



Explosion Characteristics of Blast Furnace Gas

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Abstract

The main focus of this contribution is the explosion characteristics and hazards arising from the blast furnace gas. Primarily, these are the hazards of fire and explosion induced by flammable components of blast furnace gas. In order to prevent explosions when storing and handling blast furnace gas it is necessary to know the explosion limits of individual gas components and its gas mixtures in mixture with air. However, blast furnace gas from different blast furnace can vary significantly in its composition. Therefore, for each gas composition the explosion limits would have to be determined. This would require a considerable amount of time and effort. Due to this fact, the explosion limits of blast furnace gas are frequently referred to only by the hydrogen fraction of the gas mixture in the safety-relevant literature. In reality as blast furnace gas consists of hydrogen, carbon monoxide, carbon dioxide and further residual gases the explosion limits are generally over or underestimated.

Keywords: maximum explosion pressure, constant volume adiabatic temperature, blast furnace gas

Introduction

Growth of worldwide production of iron and steel in previous years has led to the increased influence of metallurgy (Vereš et al., 2012, 2015). During the iron making process, where iron ore is reduced with coke into metallic iron a blast furnace gas (BFG) is produced as a “free” by-product (Vereš et al., 2011). The operation of such plants could be responsible for a significant number of accidents. The characteristic safety parameter of blast furnace gas in a closed vessel explosion, so called explosion characteristic, discussed in this contribution is the maximum explosion pressure. The maximum explosion pressure is the highest explosion pressure over the flammable range in a closed volume at a given fuel concentration (Eckhoff, 2005). These explosion characteristics are important for design of safety devices (e.g. relief systems, vents), able to ensure active protection of pressure vessels where flammable mixtures are formed. Beyond safety devices, the values of these parameters are useful for emergency planning especially for developing scenarios where emergency relief or external heat transfer may be inadequate. At the same time, the maximum explosion pressure that the explosion reaction can generate is one good measure of the magnitude of the hazard associated with the reaction (CCPS, 1995). The present contribution presents absolute explosion pressures (in terms of bar(a)) of fuel lean, stoichiometric and fuel rich H₂/CO/CO₂/O₂/N₂ blast furnace gas mixtures with air calculated for various initial temperatures and pressures. The aim of this contribution is to evaluate the influence of

the temperature on the explosion parameters, namely maximum explosion pressure, of the blast furnace gas that is formed in the smelting operation. The primary outcomes are: explosion parameters at ambient conditions and elevated temperatures and pressures.

Materials and methods

Figure 1 gives the schematic view of the experimental setup. It is composed of ignition system, heating system, constant volume vessel, data acquisition system and inlet/exhaust system. The explosion vessel was equipped with a piezoelectric 10 bar pressure transducer connected to the data acquisition system for measuring the explosion data, a piezoelectric 2 bar pressure transducer to adjust the initial pressure, an ignition source and lines for evacuating the vessel, feeding the blast furnace gas/air mixture and exhausting the burned mixture. A series of induction sparks generated between stainless steel electrodes was used as an ignition source. The tips of the electrodes were positioned at the centre of the vessel. The distance between the tips was (5±0.1) mm. The mounting of the electrodes was resistant to the heat and pressure generated during the tests and provided adequate electrical resistance from the test explosion vessel. A high voltage transformer (root mean square: 13–16 kV; short circuit current: 20–30 mA) was used for producing the series of ignition sparks. The blast furnace gas was metered by using a volumetric pump; the air was metered by using a mass-flow controller.

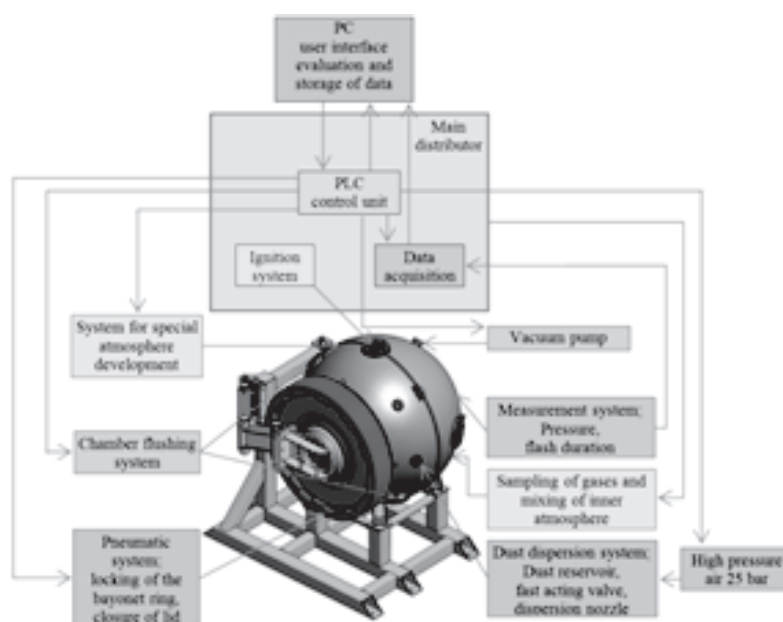


Fig. 1. Experimental set-up; schematic view

Rys. 1. Instalacja doświadczalna, schemat

Tab. 1. The compositions of blast furnace gas for theoretical predictions and experiments

Tab. 1. Skład gazu wielkopiecowego dla rozważań teoretycznych i eksperymentów

Ingredients	H ₂	CO	CO ₂	N ₂
Content vol. %	4.08±0.058	21.59±0.180	22.46±0.180	51.87±0.180

The explosion vessel and the mixing chamber were evacuated to a pressure 62 mbar, filled slowly with the gas and air mixture to 1 bar, purged by 2 times its volume and then, if necessary, the initial pressure was reduced again to the desired one. Before ignition, the mixture was allowed to become quiescent and thermally equilibrated (3–5 min). Care was taken not to warm up the equipment by explosions which were too frequent. The BFG–air mixtures were prepared by mixing together flows of air and BFG gas. The pressure measuring system (pressure transducer (Kistler), the amplifier (Kistler) and the recording system (Promotic)) fulfil the requirements of EN 13673-1 and EN 1839. Normally three tests for each composition were carried out except where the relative standard deviation is higher than that found with the test series of 6 tests performed. The mixture composition investigated and based on the real monitoring data is given in Table 1.

The mixture composition was obtained commercially in the form of pressurized bottles from SIAD and was used without further purification. The mixture was proven by analysing the flammable substance content for the test mixture and controlled by the portable GAS 3100R SYNGAS Analyser (G.E.I.T. EUROPE, Belgium; SN: 112091). Test mixture lies within an uncertainty of measurement of ±10% relative for a flammable substance content up to 2 mol%, and +0.2% absolute for a flammable substance content above 2 mol% according to EN 13673-1. BFG–air

mixtures with fuel concentrations between 30.0 and 40.0 vol.% (equivalence ratio between 0.54 and 2.26) were investigated at initial pressures (p_0) between 0.9 bar and 1.0 bar and initial temperatures between $T_0 = 298$ K and $T_0 = 308$ K.

Due to the complexity of the involved physical phenomena and to the lack of an adequate amount of reliable experimental data, a number of different models and calculation procedures for estimating the physical consequences following the physical explosion of a gaseous state are presently reported in the literature. Two computational approaches have been used for explosion pressure, Pad, calculations in this study. The element potential approach in the thermochemical equilibrium calculations applied in the Chemkin 3.6.2 subroutine using the species and their thermodynamic values from the GRI 3.0 and Konnov 5.0 (Pekalski et al., 2005) and the combustion equilibrium calculations by program GASEQ 0.79 obtained from the properties of the reactant species and of equilibrated adiabatic products using the species and their thermodynamic values from the Burcat.thr. Both chemical equilibrium models assumes adiabatic conditions in constant volume, and formation of equilibrium-defined concentrations of post explosion compounds and their expansion due to the temperature rise caused by the liberated heat assuming ideal gas behaviour. This approach represents ideal deflagrations in closed systems well and gives the highest possible

Tab. 2. Maximum explosion pressure of flammable blast furnace gas components [G = GESTIS-Substance database (IFA); EN = standard EN 13673-1; Y = Yaws' Critical Property Data for Chemical Engineers and Chemists (Knovel); D = Design Institute for Physical Properties (AiChE).]

Characteristic	Abbreviation	Unit	H ₂	CO
Maximum explosion pressure	P _{max}	bar(a)	8.3 ^G	8.2 ^G
			8.2 ^{EN}	8.3 ^Y
			7.9 ^D	8.0 ^D

Tab. 2. Maksymalne ciśnienie wybuchu łatwopalnych składników gazu wielkopiecowego [G = GESTIS-Baza danych substancji (IFA); EN = norma EN 13673-1; Y = Dane dotyczące właściwości krytycznych dla inżynierów i chemików (Knovel); D = Dane wg. Institute for Physical Properties (AiChE).]

Tab. 3. Computed explosion pressures, p_{ex}, and temperatures, T_{ad}, for H₂/CO/CO₂/O₂/N₂ mixtures at p₀ = 1 bar(a)

Tab. 3. Obliczone ciśnienia wybuchu, p_{ex} i temperatury, T_{ad}, dla mieszanki H₂/CO/CO₂/O₂/N₂ przy p₀ = 1 bar (a)

Fuel fraction [vol.%]	Initial temperature (K)							
	298		358		418		478	
	P _{ex}	T _{ad}	P _{ex}	T _{ad}	P _{ex}	T _{ad}	P _{ex}	T _{ad}
15.0	2.5±0.1	770±5	2.3±0.1	822±5	2.1±0.1	874±5	1.9±0.1	926±5
35.0	4.1±0.1	1279±5	3.5±0.1	1325±5	3.1±0.1	1370±5	2.8±0.1	1416±5
55.0	5.3±0.2	1707±10	4.5±0.2	1748±10	4.0±0.2	1790±10	3.6±0.2	1832±10
75.0	4.3±0.1	1356±5	3.7±0.1	1399±5	3.3±0.1	1444±5	3.0±0.1	1489±5

Tab. 4. Computed explosion pressures for H₂/CO/CO₂/O₂/N₂ mixtures with air at T₀ = 298 K

Tab. 4. Obliczone ciśnienia wybuchu dla mieszanki H₂/CO/CO₂/O₂/N₂ z powietrzem T₀ = 298 K

Fuel fraction [vol.%]	Initial pressure (bar(a))							
	1		5		10		15	
	P _{ex}	T _{ad}	P _{ex}	T _{ad}	P _{ex}	T _{ad}	P _{ex}	T _{ad}
15.0	2.5±0.1	770±5	12.7±0.1	770±5	25.3±0.1	770±5	38.0±0.1	770±5
35.0	4.1±0.1	1279±5	20.5±0.1	1283±5	41.0±0.1	1289±5	61.5±0.1	1298±5
55.0	5.3±0.2	1707±10	26.6±0.2	1712±10	53.2±0.2	1736±10	79.9±0.2	1758±10
75.0	4.3±0.1	1356±5	21.5±0.1	1365±5	43.1±0.1	1376±5	64.6±0.1	1389±5

attainable explosion pressures. It has been shown that the model is able to predict, with a reasonable accuracy, the experimental values of the explosion pressures and constant volume adiabatic explosion temperatures also in different fuel-enriched conditions, for different types of gaseous explosions (Skrinsky et al., 2016a,b).

Results and discussion

Results of explosion experiments depend on many different parameters of the investigated process, such as the energy and type of ignition source, size and shape of explosion chamber, initial temperature, initial pressure and composition of the flammable mixture. To ensure the compatibility of data we selected the results for experiments that are in agreement with EN 13673-1. The results of theoretical predictions and experiments are summarized in Table 2–5.

A) Experimental and theoretical P_{max} for H₂/CO/CO₂/O₂/N₂ at ambient temperature and pressure

Table 2 compares the theoretically derived data for the maximum explosion pressure of the studied blast furnace gas mixture components. The values were adopted from the databases as the IFA and the AiChE, and from the literature (EN 13673-1, 2003 and Yaws, 1999).

B) Theoretical P_{max} for H₂/CO/CO₂/O₂/N₂ at elevated temperature and pressure

Computed adiabatic temperatures, T_f, and maximum explosion pressures, p_{max}, for blast furnace gas-air mixtures (15.0 vol. %, 35.0 vol. %, 55.0 vol. %, 75.0 vol. %) at various initial temperatures, T_{init}, and ambient initial pressure are given in Table 3 and Figure 2a,b. The values of uncertainty denotes the mean difference between the results of two computational approaches used in this study and is in agreement with (Pekalski et al., 2005).

From the numerical results of Table 3 it is possible to identify that the increase in the initial temperature lowers the maximum explosion pressure, and increases the flammability range of BFG/air mixture.

The value of the explosion pressure with varying H₂/CO/CO₂/O₂/N₂ concentration is similar at all investigated initial temperatures. The maximum value of the explosion pressure is found close to 62.5 vol. % of BFG for all conditions. Further, in Table 4 and Figure 3a,b, we reported simulations on the explosion properties of H₂/CO/CO₂/O₂/N₂ mixtures at various initial pressure and ambient initial temperature.

From the data performed in Table 4, it is clear that the increase of initial pressure has significant effect on explosion pressure when only the air served as oxidant. This is a

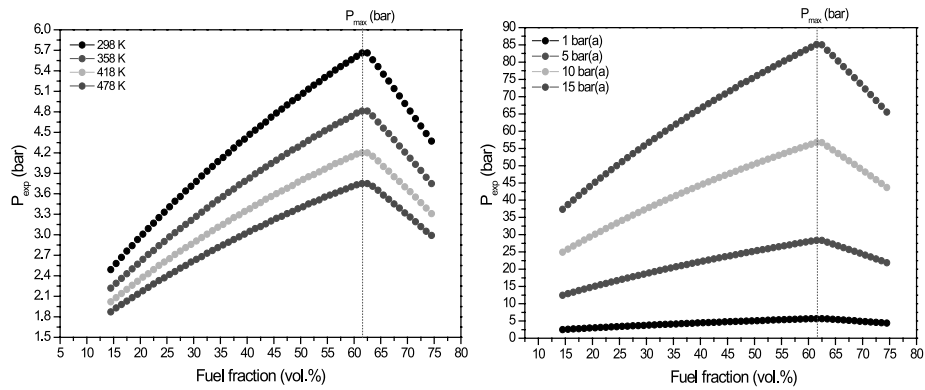


Fig. 2. Calculated explosion pressure vs fuel fraction for explosions of a) $H_2/CO/CO_2/O_2/N_2$ mixture with air at 298 K (top), 358 K (upper middle), 418 K (lower middle), and 478 K (bottom); b) $H_2/CO/CO_2/O_2/N_2$ with air mixture at 1 bar(a) (top), 5 bar(a) (upper middle), 10 bar(a) (lower middle), and 15 bar(a) (bottom)

Rys. 2. Obliczone ciśnienia wybuchu w zależności od udziału paliwa dla wybuchu a) dla mieszanki $H_2/CO/CO_2/O_2/N_2$ z powietrzem $T_0 = 298$ K, 358 K (wyższa średnia), 418 K (niższa średnia) i 478 K (dno); b) dla mieszanki $H_2/CO/CO_2/O_2/N_2$ z powietrzem 1 bar (a) góra, 5 bar (a) wyższa średnia, 10 bar(a) niższa średnia i 15 bar (a) (dno)

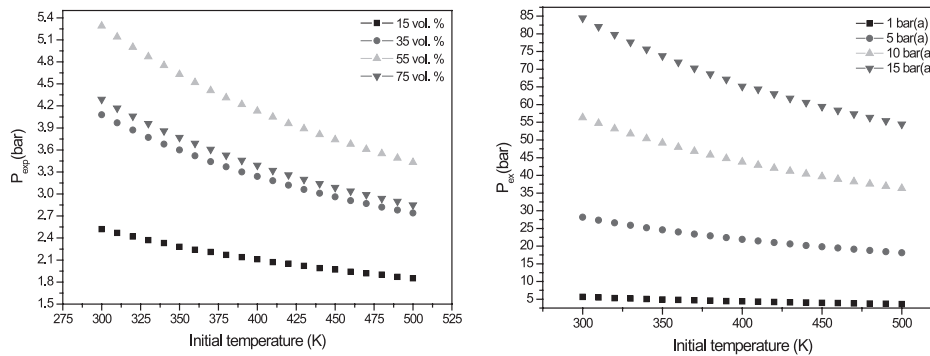


Fig. 3. Calculated explosion pressure vs initial temperature for explosions of a) $H_2/CO/CO_2/O_2/N_2$ mixture with air at 15.0 vol. % (top), 35.0 vol. % (upper middle), 55.0 vol. % (lower middle), and 75.0 vol. % (bottom); b) $H_2/CO/CO_2/O_2/N_2$ mixture with air at 1 bar(a) (top), 5 bar(a) (upper middle), 10 bar(a) (lower middle), and 15 bar(a) (bottom)

Rys. 3. Obliczone ciśnienia wybuchu w zależności od temperatury wybuchu dla: a) mieszaniny $H_2/CO/CO_2/O_2/N_2$ z powietrzem 15.0 vol. % (górze), 35.0 vol. % (wyższa średnia), 55.0 vol. % (niższa średnia) i 75.0 vol. % (dno); b) mieszaniny $H_2/CO/CO_2/O_2/N_2$ z powietrzem przy 1 bar(a) (górze), 5 bar(a) (wyższa średnia), 10 bar(a) (dolna średnia) i 15 bar(a) (dno)

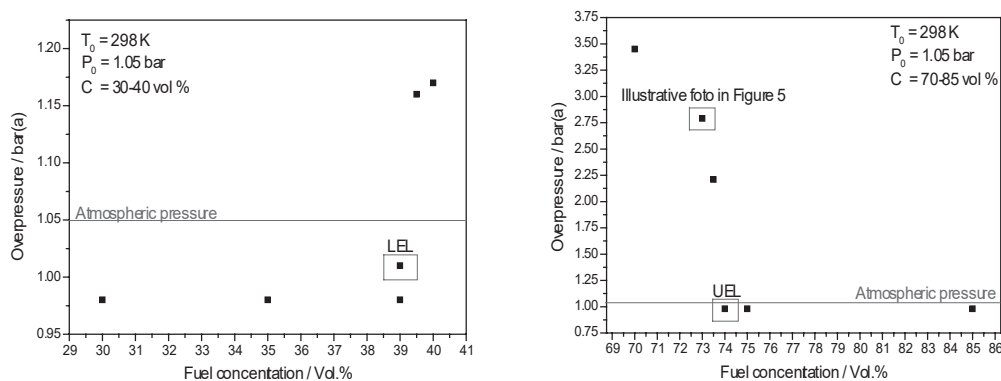


Fig. 4. Results of flammability limits measurements for $H_2/CO/CO_2/O_2/N_2$ mixtures with air at $T_0 = 298$ K

Rys. 4. Wyniki pomiarów limitów palności dla mieszanin $H_2/CO/CO_2/O_2/N_2$ z powietrzem przy $T_0 = 298$ K



Fig. 5. Illustrative photo for 73.0 vol. % of H₂/CO/CO₂/O₂/N₂ mixture with 27.0 vol. % of air at T₀ = 298 K: a) early stage of explosion initiation; b) end of ignition process.

Rys. 5. Zdjęcie poglądowe dla 73,0 % obj. mieszaniny H₂/CO/CO₂/O₂/N₂ z 27,0% obj. powietrza w T₀ = 298 K: a) wczesny etap inicjacji wybuchu; b) koniec procesu zapalania

Tab. 5. Flammability limits of blast furnace gas components, all values are in vol. % [G = GESTIS-Substance database (IFA); D = Design Institute for Physical Properties (AiChE); Y = Yaws' Critical Property Data for Chemical Engineers and Chemists (Knovel)]

Tab. 5. Granice zapalności składników gazu wielkopiecowego, wszystkie wartości podano w% obj. [G = GESTIS-Baza danych substancji (IFA); D = dane Institute for Physical Properties (AiChE); Y = Wartości krytyczne YAW's dla inżynierów i chemików (Knovel)]

Characteristic	Abbreviation	Unit	H ₂	CO
Lower explosion limit	LEL	bar(a)	4.0 ^G	11.3 ^G
			4.0 ^D	12.5 ^D
			4.0 ^Y	12.5 ^Y
Higher explosion limit	UEL	bar(a)	77.0 ^G	75.6 ^G
			75.0 ^D	74.0 ^D
			75.0 ^Y	74.0 ^Y

good approximation at initial pressures i.e. up to 15 bar(a), but we may assume that will be increasing wrong at higher pressures.

C) Flammability limits of H₂/CO/CO₂/O₂/N₂ mixtures with air at T₀ = 298 K

Previous studies on LEL and UEL are summarized in Table 5. From the data performed in Table 5, it is clear that the values of LEL are the same for H₂ but differs for CO (from 11.3–12.5 vol. %). The values of UEL for CO differs from 74.0–75.6 vol. %. In both cases is the value of UEL for CO behind the reproducibility of 0.2 vol. % required by EN 1839.

The values shown in Figure 4a,b are valid only for the conditions under which they were determined (room temperature and atmospheric pressure using a 1000-L explosion vessel with hot-wire ignition). Figure 5 illustrates the early stage (Figure 5a) and end (Figure 5b) of explosion (73.0 vol.% of H₂/CO/CO₂/O₂/N₂ mixture with 27.0 vol. % of air at T₀ = 298 K). In both photos the characteristic vortex closed to the ignition point in the middle of the vessel is observed. Because the concentration is very close to the upper explosion limit, the flame front could be observed and is not destroyed by the pressure increase.

Conclusion

The adiabatic explosion pressures of H₂/CO/CO₂/O₂/N₂ mixture with air at various initial temperatures and pressures were calculated together with the measurements

of LEL and UEL. The model predictions for the blast furnace gas mixtures are compared for four different initial temperatures. Although the results from the evaluation indicate that presented theoretical simulations can become a valuable tool for rough estimation, the modelling requires further improvements to be useful for consequence modelling and design of industrial facilities. Thus, at the first stage, the equilibrium calculations can be used as a rough calculation of a worst case scenario. At the same time, these values could be used as initial values for further explosion experiments carried out in heated 1 m³ explosion apparatus designed by OZM Research s.r.o. at Energy Research Centre, VŠB - Technical University of Ostrava. As the practical outcome these results will apply for the iron making processes, where iron ore is reduced with coke into metallic iron and the explosive BFG is formed. The results represents a continuation of numerous efforts by various research groups, where the key underlying problem has been the understanding of results obtained in laboratory tests for predicting the consequences of multicomponent gas mixture explosion scenarios in industry (Skrinsky et al., 2015).

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Literatura – References

1. VEREŠ, Ján et al. Zinc recovery from iron and steel making wastes by conventional and microwave assisted leaching. *Acta Montanistica Slovaca* 16, 2011, p. 185-191, ISSN 1335-1788.
2. VEREŠ, Ján et al. Chemical, mineralogical and morphological characterisation of basic oxygen furnace dust. *Transactions of the Institutions of Mining and Metallurgy, Section C: Mineral Processing and Extractive Metallurgy* 124, 2015, p. 1-8, ISSN 0371-9553.
3. VEREŠ, Ján et al. Characterization of blast furnace sludge and removal of zinc by microwave assisted extraction. *Hydrometallurgy* 129, 2012, p. 67-73, ISSN 0304-386X.
4. ECKHOFF, Rolf. *Explosion Hazards in the Process Industries*, 1st edition. Gulf Publishing Company, Houston, 2005, p. 436, ISBN 97-809-7651-1342.
5. CCPS (Center for Chemical Process Safety). *Guidelines for Safe Storage and Handling of Reactive Materials*. American Institute of Chemical Engineers, New York, 1995. 364 p.
6. PEKALSKI, Andrzej et al. Determination of the explosion behaviour of methane and propene in air or oxygen at standard and elevated conditions. *Process Safety and Environmental Protection* 83, 2005, p. 421-429, ISSN 0957-5820.
7. SKŘÍNSKÝ, Jan et al. Explosion characteristics of methane for CFD modeling and simulation of turbulent gas flow behavior during explosion. *AIP Conference Proceedings* 1745, 2016a, ISSN 0094-243X.
8. SKŘÍNSKÝ, Jan et al. Explosions caused by corrosive gases/vapors, *Materials Science Forum* 844, 2016b, p. 65-72, ISSN 0255-5476.
9. GESTIS-Substance database. Institut für Arbeitsschutz der Deutschen Gesetzlichen Unfallversicherung (IFA), 2015.
10. EN 13673-1. Determination of maximum explosion pressure and maximum explosion pressure rise - Part I: maximum explosion pressure 2003, European Standard.
11. YAWS, Carl. *Chemical Properties Handbook: Physical, Thermodynamics, Environmental, Transport, Safety & Health Related Properties for Organic & Inorganic Chemicals*, 1st edition, McGraw-Hill, New York, 1999, p. 784, ISBN 1606235273 .
12. Design Institute for Physical Properties, DIPPR Project 801 – Full Version, Design Institute for Physical Property Research/AIChE, 2016.
13. SKŘÍNSKÝ, Jan et al. Flashpoint prediction for binary mixtures of alcohols with water in order to improve their safety, *Chemical Engineering and Technology* 38, 2015, p. 727-733, ISSN 0930-7516.

Charakterystyka wybuchowa gazu wielkopiecowego

Celem artykułu jest charakterystyka i zagrożenia wynikające z wybuchu gazu wielkopiecowego. Nie-bezpieczeństwo pożaru i wybuchu wywołane jest przez łatwopalne składniki gazu wielkopiecowego. Aby zapobiec wybuchom w trakcie powstawania gazu wielkopiecowego konieczne jest poznanie granic wybuchowości poszczególnych składników gazu i mieszanin gazowych z powietrzem. Gaz wielkopiecowy z różnych wielkich pieców może się znacznie różnić pod względem składu. W związku z tym, dla każdego składu gazu należy określić granice wybuchowości. Wymaga to znacznego czasu i wysiłku. Z tego powodu granice wybuchu gazu wielkopiecowego są często określane (w literaturze dotyczącej bezpieczeństwa) tylko przez zawartość frakcji wodorowej w mieszaninie gazowej. W rzeczywistości gaz wielkopiecowy składa się z wodoru, tlenku węgla, dwutlenku węgla i innych gazów resztkowych. Granice wybuchowości są generalnie przekroczone.

Słowa kluczowe: maksymalne ciśnienie wybuchu, stała objętość, temperatura adiabatyczna, gaz wielkopiecowy