Explosion Characteristics of Syngas from Gasification Process

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Abstract

This paper describes a series of experiments performed to study the explosion parameters of syngas and its flammable component air mixtures. More than 100 pressure-time curves were recorded allowing to investigate the effects of three different gasification process conditions on the maximum explosion pressure and deflagration index. The representative syngas samples were prepared by thermochemical wood-pellets gasification. The experiments were performed in 20-L oil-heated spherical experimental arrangement for different concentrations at representative explosion initial temperature of 65°C. The experimental results were further compared with the explosion parameters of pure gases, namely hydrogen, methane, carbon monoxide and propane as the main flammable syngas components. The most important results are the maximum values of explosion pressure 7.2 ± 0.2 bar and deflagration index 170 ± 14 bar.m/s derived for start-up process conditions. These knowledge could be used to understand the effects of operating conditions to both the optimization design on syngas-fueled applications and the safety protection strategies.

Keywords: *explosion parameter, carbon monoxide, hydrogen, methane, propane, syngas, vessel*

Introduction

Due to its many significant advantages as a fuel in stationary power generation, syngas is a candidate among the alternatives being explored for energy conversion and to produce liquid biofuels from renewable resources (Saad and Williams, 2017). Apart from the alternative fuel interest, the non-standard operation regime of such process could lead to an explosion. The composition of syngas from gasification unit vary significantly with different operation conditions. Therefore, for main operating conditions the explosion parameters would have to be determined. In the literature the syngas composition is frequently referred to only stable operation condition. As a result, the explosion parameters are generally underestimated (Skrinsky, 2018). Small-scale characterization of the syngas explosion parameters over a range of fuel concentrations, temperatures and pressures has been published starting from 2014. Sarli et al. presents the pmax = 4.7–5.9 and K_G = 9.4 – 35.6 bar.m/s of wood chip-derived syngas at 283 K.

The study was performed in 5-L cylindrical vessel at two initial temperatures, 283 K and 573 K, and at atmospheric pressure (Sarli et al., 2014). Xie et al. studied the pressure history in the explosion syngas/air mixtures with H_2O addition. The maximum values have been determined p_{max} = 5.1–5.9 and K_G = 65–225 bar.m/s measured in 5-L cylindrical vessel at 373 K (Xie, 2016). Skrinsky et al. presents the results of an experimental evaluation of the safety characteristics for syngas stable operation conditions at temperatures of 323 K, 373 K and 423 K and at elevated pressures of 0.50 bar, 0.75 and 1.00 bar (Skrinsky, 2018). He evaluated the values of p_{max} = 5.4–7.0 bar and KG = 45–63 bar.m/s at 20-L oil-heated spherical experimental arrangement. Tran et al. described the influence of hydrocarbon additions and dilutions on explosion behavior of syngas/air mixtures. In his study, explosion behaviors of hydrocarbon-added and diluted syngas/air mixtures were investigated experimentally in a 6.9-L constant volume combustion chamber (Tran, 2017). The explosion parameters have been found p_{max} = 8.3–9.2 bar and K_G = 238–467 bar.m/s at 298 K. The goal of this paper is to investigate the effect of initial process conditions on explosion parameters of syngas-air mixture. The practical aim of interest is to explore if the substantial variation in syngas composition due to different gasification conditions will cause a significant influence on the explosion parameters and which gasification regime is among the most dangerous.

Materials

The average composition of syngas produced for the explosion experiments are summarized in Table 1.

Syngas consists of flammable hydrogen (H_2), methane (CH_4), carbon monoxide (CO), and propane (C_3H_8). It is diluted with inert constituents of carbon dioxide (CO_2) and nitrogen (N_2) which results in decrease of the flammability range. The synthetic gas has been produced by gasification of a carbon containing lignocellulose biomass fuel (wood pellets). Wood pellets is one of the main organic materials used as gasification feedstock (Sarli et al, 2014). The small scale autothermal gasification technology (Temex Ltd., Czech patent no. 304091) is described schematically in Figure 1 (reproduced with permission from (Čespiva, 2018).

The goal of this technology is the research and development of the biomass gasification process. The gasification reactor (gasifier) with a fixed bed, operates in an autothermal mode with heat output up to 100 kW, gasification ratio is be-

Tab. 1. The average composition (in vol. %) of syngas produced for the experiments (dry basis)
Tab. 1. Średni skład (w % obj.) gazu syntezowego wyprodukowanego dla potrzeb eksperymentu (sucha podstawa)

Chemical	H_2	CH_4	CO	C_3H_8	CO_2	O_2	N_2
Start-up	6.0	3.5	22.0	0.6	8.0	1.0	58.9
Process	17.1	1.3	20.0	1.2	11.8	0.1	48.5
Shut-down	5.5	4.5	21.0	0.6	7.0	2.0	59.4

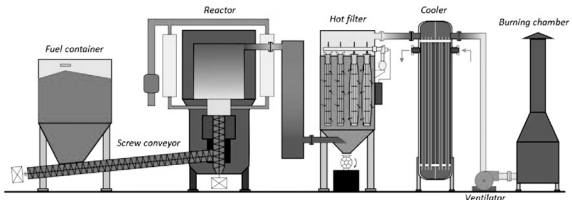

Fig. 1a. Schematic introduction of the ERC´s autothermal gasification technology
Rys. 1a. Wstęp schematyczny do technologii autotermiczego zgazowania ERC

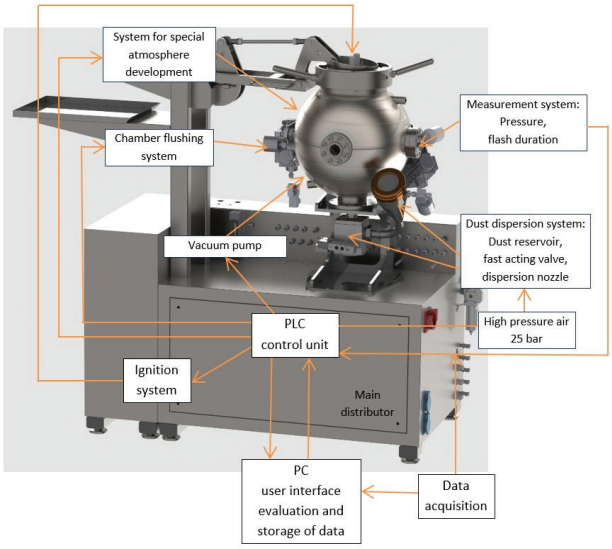

Fig. 1b. Scheme of the 0.02 m^3 experimental set-up
Rys. 1b. Schemat ustawienia eksperymentalnego 0,02 m^3

tween 0.2–0.4 (fuel to gas) and gasification temperature between 850–1000°C. Syngas was measured after pre-treatment on dry basis and at ambient temperature. The composition of gaseous alkanes, carbon monoxide, hydrogen, oxygen and carbon dioxide at ambient temperature were measured by the portable Syngas analyzer (Pollutek, GAS 3000P, Pellenberg, Belgium) with resolution 0.01 vol. %. The subsequent utilization (filter, cooling with water) of the produced synthetic gas depends on its quality and content of undesirable components. All the pure gas samples have the purity higher than 99.8 mass %.

Methods

The experiments have been performed in a constant volume stainless steel double wall vessel of spherical shape with an internal diameter of 336 mm (SN: 497-OZM-15, OZM Research, s.r.o., Hrochův Týnec, Czech Republic) adopted for the high-temperature experiments. The set-up consists of spherical vessel, cooling system, spark generator, and data acquisition system. Digitally adjustable temperature control device Presto A 30 (SN: 10291377, JULABO GmbH, Seelbach, Germany) has been used to heat the oil in the instrument to the specified temperature close to the expected. Temperature control system has been used to heat the system of the vessel up to 65 °C. The system allows to hold the internal vessel temperature 65°C with a temperature fluctuation of less than 2°C. The initial temperature in time of ignition has been measured using the calibrated thermocouple (SN: 10291377, Jakar, Karviná, Czech Republic) with an accuracy 0.5°C located on the top of the explosion vessel (Skrinsky and Ochodek, 2019).

The data acquisition system comprises the pressure sensors, transducer sensors, signal conditioning system and signal convertor system connected to PC. The explosion pressures have been recorded by pair of piezoelectric pressure sensors (SN: 4512821 and SN: 4512822, model 701A, Kistler, Winterthur, Switzerland) and with a transducer sensor charge amplifier (Kistler, model 5041E1). Operating temperature range of the sensors is from -150°C to 200°C that is satisfactory for presented experiments. The calibrated partial range for the sensors is from 0 bar to 20 bar. The signal conditioning module (Tedia, model UDAQ-3644) has worked at a sampling frequency 50 kHz with a sampling period of 0.02 ms with a high resolution 16-bit A/D convertor connected to PC´s USB. Whole acquisition is controlled by user interface PROMOT-

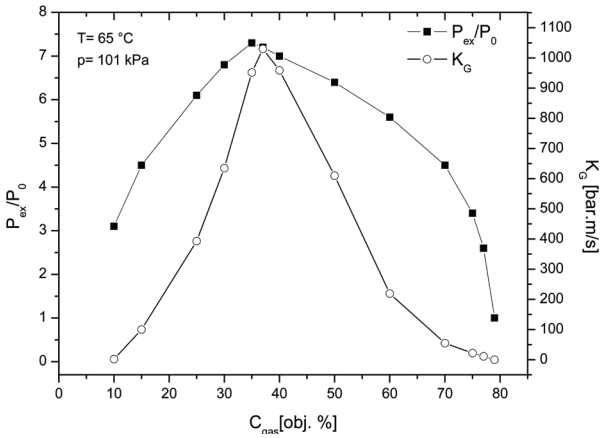

Fig. 2. P_{ex}/P_0 and K_G versus concentration for H_2
Fig. 2. P_{ex}/P_0 oraz KG w układzie ze stężeniem H_2

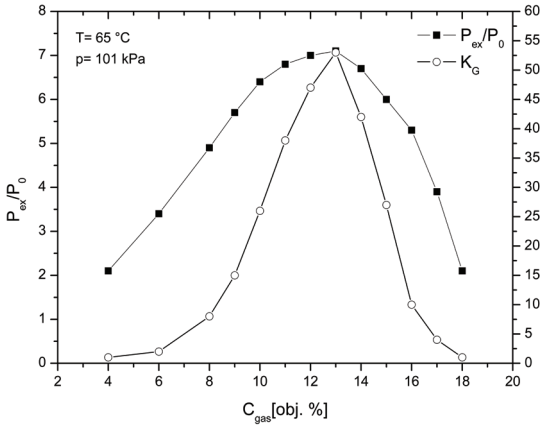

Fig. 3. P_{ex}/P_0 and K_G versus concentration for CH_4
Fig. 3. P_{ex}/P_0 oraz KG w układzie ze stężeniem CH

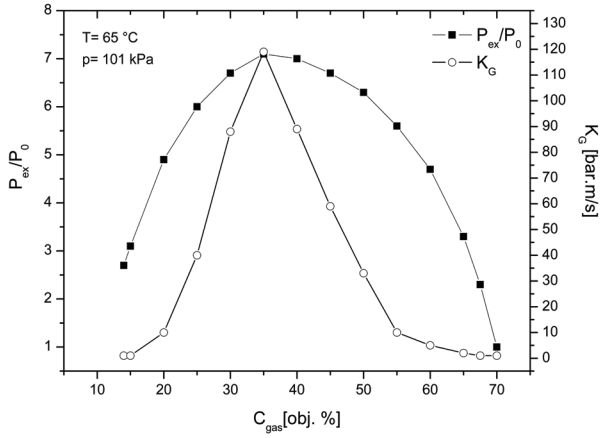

Fig. 4. P_{ex}/P_0 and K_G versus concentration for CO
Fig. 4. P_{ex}/P_0 oraz KG w układzie ze stężeniem CO

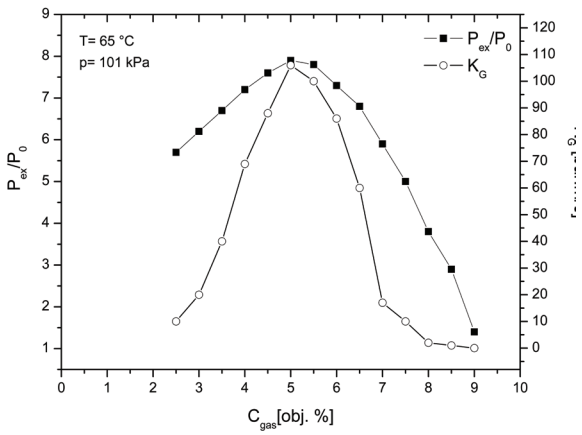

Fig. 4. P_{ex}/P_0 and K_G versus concentration for C_3H_8
Fig. 4. P_{ex}/P_0 oraz KG w układzie ze stężeniem C_3H_8

IC system (MICROSYS, spol. s.r.o., Ostrava, Czech Republic). Programmable logic control station (model 5073A211, Simatic, Siemens, Munich, Germany) connected to PC have been adapted to automatically control procedures for partial pressure method (gas feeding), fast acting valve timing and bottom rotating fan ensuring mixing of the fuel with air mixture. The mixture was ignited by the electric discharge from permanent spark generator (10 J) with ignition delay time 60 ms. The rods of the electrodes are positioned in the center of the testing vessel with the distance between the tips of 5 mm. The spark discharge time is adjusted to 200 ms (Skrinsky and Ochodek, 2019). The whole system is schematically introduced at Figure 1.

The methodology being applied to investigate the explosion parameters is based upon the European Standard EN 15967:2011. This method allows the measurement at atmospheric conditions and have been adapted for high temperature studies. Syngas test mixture is ignited by a defined ignition source which is positioned in the center of a test vessel. By means of a pressure measuring system, the highest pressure pex developed following the ignition of the test mixture is measured. The maximum explosion pressure pmax is determined during measurements of the explosion pressure pex by varying stepwise the content of flammable gas in the mixture, until the maximum value of pex is found. The pressure-time curve developed following ignition of the test mixture is recorded and the highest rate of explosion pressure rise $(dp/dt)_{ex}$ is calculated as the derivation. The maximum rate of explosion pressure rise $(dp/dt)_{max}$ is normalized to vessel volume by which the deflagration index is found (EN 15967:2011).

Results and discussion

Figures 2–5 plot the atmospheric pressure normalized explosion pressure (P_{ex}/P_0) and the deflagration index (K_G) versus concentration. Both parameters are measured for pure hydrogen, pure methane, pure carbon monoxide, and pure propane at initial temperature (65°C) and ambient initial pressure (101 kPa).

All the explosion pressure curves of the individual syngas flammable components possess a similar behavior. The pressure and deflagration index increases until reaching its maximum value at stoichiometric concentration and then decreases due to heat loss. The results of the P_{ex}/P_0 and K_G versus concentration for the hydrogen (H_2), methane (CH_4), carbon monoxide (CO), and propane (C_3H_8) are summarized in Table 2.

The data evaluation is well described in (Skrinsky and Ochodek, 2019). The experimental uncertainty in a statistical sense is given by the used experimental method and is ac-

Tab. 2. Average values of the explosion parameters at t_0 = 65°C and p_0 = 101 kPa
Tab. 2 Średnie wartości parametrów eksplozji dla t_0 =65°C oraz p_0 =101 kPa

Characteristic	Unit	H_2	CH_4	CO	C_3H_8
P_{max}/P_0	[–]	7.3 ± 0.2	7.1 ± 0.2	7.1 ± 0.2	7.9 ± 0.2
K_G	[bar▪ m/s]	1030 ± 82	53 ± 4	119 ± 10	106 ± 9

Tab. 3. Average values of the explosion characteristics at Φ = 1,0 and p_0 = 101 kPa
Tab. 3. Średnie wartości charakterystyk eksplozji dla Φ = 1,0 oraz P_0 = 101 kPa

Characteristic	Unit	Start-up	Stable	Shut-down
P_{max}/P_0	[–]	7.1 ± 0.2	6.8 ± 0.1	7.0 ± 0.2
K_G	[bar▪ m/s]	170 ±14	147 ± 12	159 ± 13

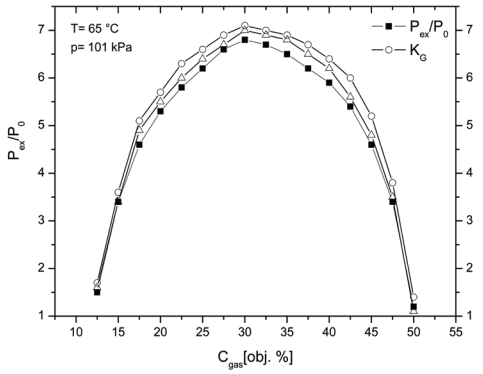

Fig. 6. P_{ex}/P_0 at C=12.5-50.0 vol. %, P_0=101 kPa and T0= 65°C for syngas-air mixtures
Rys. 6. P_{ex}/P_0 dla C=12,5-50,0 % obj., P_0 =101 kPa, T 0 =65°C dla mieszaniny powietrza i gazu syntezowego

Fig. 7. K_G at C=12.5-50.0 vol. %, P_0=101 kPa and T0= 65°C for syngas-air mixtures
Rys. 7. K_G dla C=12,5-50,0 % obj., P_0 =101 kPa, T0 =65°C dla mieszaniny powietrza i gazu syntezowego

cording to EN 15967:2011. It has been well established that a progressive change occurs in the variety of some explosion properties of gases when mixed them together. A very interesting example of such differences is given by Figure 6–7 for three different H_2-CH_4-CO-C_3H_8-air mixtures compositions from Table 1. The search for the explosion parameters of the syngas was initiated in the concentration range from 10 vol. % up to 50 vol. % where the lowest explosion pressure has been expected according to previous studies (Skrinsky, 2018).

We consequently focused on the determination of maximum explosion parameters in the region close to C = 50.0 vol. % according to our previous calculations (Skrinsky, 2018). After several attempts consisting in adjusting the experimental apparatus, they were found close to C = 30.0 vol.%. The results of the Pex/P0 and KG versus concentration for three operational regimes of gasifier are summarized in Table 3.

Conclusion

The most important results of the presented experiments is the analysis of syngas-air mixture explosion behaviour at specific gasification process conditions. Explosion pressure and deflagration index of the syngas-air mixtures were determined in the 0.02 m3 closed spherical vessel for the three different gasification process regimes start-up, stable and shut-down.

The main conclusions are summarized as follows:

1. Among syngas–air process regimes, the normalized explosion pressure and deflagration index increase in the or-

der process, shut-down and start-up at given experimental and process conditions.

2. Explosion pressure and deflagration index of the syngas mixture reach maximum values at the stoichiometric concentration C = 30.0 vol. % within the studied range from 12.5 to 50.0 vol. % at initial temperature of 65°C and initial pressure of 101 kPa.

3. The maximum explosion pressure, pmax, was determined as the highest pex found for the mixture compositions investigated and is equal to 7.1 ± 0.2 bar.

4. The deflagration index was calculated from the experimentally determined (dp/dt)max value and is equal to 170 ± 14 bar.m/s.

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Charakterystyka eksplozji gazu syntezowego z procesu zgazowania

Artykuł opisuje serię eksperymentów wykonanych w celu zbadania parametrów eksplozji gazu syntezowego oraz jego części palnych w mieszaninie z powietrzem. Więcej niż 100 krzywych w układzie ciśnienie-czas zostało zarejestrowanych pozwalając na zbadanie efektów trzech różnych warunków procesu zgazowania przy maksymalnym ciśnieniu eksplozji i wskaźniku deflagracji. Reprezentatywne próbki gazu syntezowego zostały przygotowane za pomocą zgazowania termochemicznego drewnianych granulek. Eksperymenty zostały wykonane w podgrzewanej olejem instalacji o kształcie sferycznym, której objętość wynosiła 20 Li wykorzystana została dla różnych stężeń oraz reprezentatywnej temperatury wstępnej na poziomie 65°C. Wyniki doświadczalne były następnie porównane z parametrami wybuchu czystych gazów, którymi były wodór, metan, tlenek węgla oraz propan, jako główne składniki gazu syntezowego. Najważniejszymi wynikami okazały się maksymalne wartości ciśnienia wynoszące 7,2 ± 0,2 barów oraz wskaźnik deflagracji na poziomie 170 ± 14 bar.m/s wyznaczony dla warunków startowych procesu. Informacje te mogą zostać wykorzystane w celu zrozumienia wpływu warunków operacyjnych dla optymalizacji zastosowań gazu syntezowego oraz strategii bezpieczeństwa związanego z jego wykorzystaniem.

Słowa kluczowe: *parametry eksplozji, tlenek węgla, wodór, metan, propan, gaz syntezowy*