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Explosion Characteristics of a Biogas/air Mixtures

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An experimental apparatus for the biogas and air mixture explosion in a closed spherical vessel was set up. Biogas-air mixtures were studied experimentally and numerically for different equivalence ratios between 0.25 and 2.4, and initial temperatures of 20, 50, 75, and 100 °C. For given equivalence ratios, more than 120 pressure-time curves were recorded. The effects of temperature on the maximum explosion pressure, maximum rate of pressure rise, and deflagration index were investigated. The most important results from evaluated experiments are the deflagration index 16 bar·m/s and the maximum pressure rise of 60 bar/s for biogas–air mixtures at initial ambient conditions.

1. Introduction

Anaerobic digestion (AD) is a biochemical process via which organic material is converted into gaseous fuel (CH_4, CO_2, and H_2) by divergent consortia of microorganisms under precisely controlled anaerobic conditions. (Basinas, 2021) Due to the presence of methane, biogas is a combustible gas. Thus, its handling can cause fire and explosion hazards. Hence, knowing the biogas explosivity chart is fundamental to understanding adequate risk assessment and running biogas plants safely. There is a limited number of studies on biogas/air mixture explosion parameters. The first studies suggested biogas characteristics to be similar to those of methane. (Campbell, 1996) This assumption can hardly complicate explosive atmospheres prevention and protection measures. For example, applying appropriate explosion vent sizing is sometimes impossible when methane explosive characteristics are used rather than biogas. Dupont and Accorsi (2006) present explosion characteristics of synthesized biogas at various temperatures. Biogas explosion characteristics have been measured in a standard 20-L spherical vessel under quiescent conditions using an electric spark (10 J) ignition. The Computational Fluid Dynamic (CFD) code FLame ACcelaration Simulator (FLACs) simulated the biogas explosion based on the experimental case study. Experimental investigation of synthesized biogas explosion characteristics was conducted in a 20-L sphere at various temperatures (30–70 °C) and atmospheric pressure. The studied biogases were 50% methane (CH_4) and 50% carbon dioxide (CO_2). Chen et al. (2019) presented the Influence of N_2/CO_2 Blends on the explosion characteristics of the stoichiometric methane-air mixture. Sulaiman et al. (2020) show explosion characteristics assessment of premixed biogas-air mixture in a 20-L spherical vessel. The experimental data reported from this study concluded that P_{max} = 8–8.50 bar, the dP/dt = 100–400 bar/s and the K_G = 32.7–121 bar.m/s were recorded at equivalence ratio, (ER) = 1.2 with CO_2 composition in the biogas = 30% vol/vol. It was found that the severity of the biogas explosion increased proportionally with the biogas concentration. Skrinsky et al. (2018) presented explosion parameters of degas-air mixtures at elevated temperatures. Our investigation starts with the pure methane-air mixtures. Measured explosion parameters data (Pmax, K_G) for pure methane-air mixture at ambient initial pressure and temperature have been summarized in Mittal (2017). There have been presented results of 21 experimental studies published between 1965-2014. These studies have provided the values of Pmax (6.8 – 8.7 bar) and KG (45-80 bar.m/s) values. Different vessels shapes obtained the experimental data (cubic, cylindrical, spherical) and volumes (0.005 - 204 m^3).

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2. Experimental set-up

2.1 Explosion vessel

The experiments have been performed in a constant volume stainless steel double wall vessel of spherical shape (SN: 497-OZM-15, OZM Research, s.r.o.) adopted for the biogas-explosion experiments (Skrinsky, 2018). The set-up consists of an explosion vessel, heating system, spark generator, and data acquisition system.

2.2 Heating vessel

Digitally adjustable temperature control device Presto (SN: 10291377, JULABO GmbH, model A 30) has been used to heat the oil in the instrument to the specified temperature close to the expected. A temperature control system has been used as a heating system of the vessel up to 100 °C. The temperature ranged from 20 °C to 100 °C, with a temperature fluctuation of less than 2 °C. The initial temperature in ignition time has been measured using the calibrated thermocouple (SN: 10291377, Jakar) with an accuracy of 0.5 °C located on the top of the explosion vessel.

2.3 Spark generator

The electric discharge ignited the mixture from a permanent spark generator (15 kV, AC 20 mA) with an ignition delay time of 60 ms. The rods of the electrodes are positioned in the center of the testing vessel with a distance between the tips of 5 mm. The spark discharge time is adjusted to 200 ms.

2.4 Pressure measuring unit

The explosion pressures have been recorded by pair of piezoelectric pressure sensors (SN: 4512821 and SN: 4512822, Kistler, model 701A) and with a transducer sensor charge amplifier (Kistler, model 5041E1). The operating temperature range of the sensors is from -150 °C to 200 °C that is satisfactory for the presented experiments. The calibrated partial range for the sensors is from 0 bar to 20 bar.

2.5 Data acquisition

The data acquisition system comprises the pressure sensors, transducer sensors, signal conditioning system, and signal convertor system connected to the PC. The signal conditioning module (Tedia, model UDAQ-3644) has worked at a sampling frequency of 50 kHz with a sampling period of 0.02 ms with a high-resolution 16-bit A/D converter connected to the PC´s USB. The user interface controls the acquisition (PROMOTIC system, MICROSYS, s.r.o).

2.6 Experimental procedure

The methodology used to investigate the explosion severity and sensitivity characteristics is based on the European Standards EN 15967 (2012). These methods allow the measurement at atmospheric conditions and have been adapted for high-temperature studies. An explosive test mixture is ignited by a defined ignition source positioned in the center of a test vessel. Using a pressure measuring system, the highest pressure developed following the ignition of the test mixture is measured. The maximum explosion pressure is determined during measurements of the explosion pressure by varying stepwise the content of flammable gas in the mixture, until the maximum value is found (EN 15967, 2012).

2.7 Gas composition tested

The gas composition for these tests was produced by semi continual psychrophile digestion in two-stage vertical industrial-scale bioreactor P200 situated in Institute of Environmental Technology, VSB-TU Ostrava. The accurate gas composition was determined as three days mean by BIOGAS 500 gas monitor and is listed in Table 1.

Table 2: Composition of material used

CH_4 vol. %	CO_2 vol. %	O_2 vol. %	H_2 ppm	H_2S ppm
56.9	41.8	0.3	55	1150

The whole test assembly is schematically introduced in Figure 1.

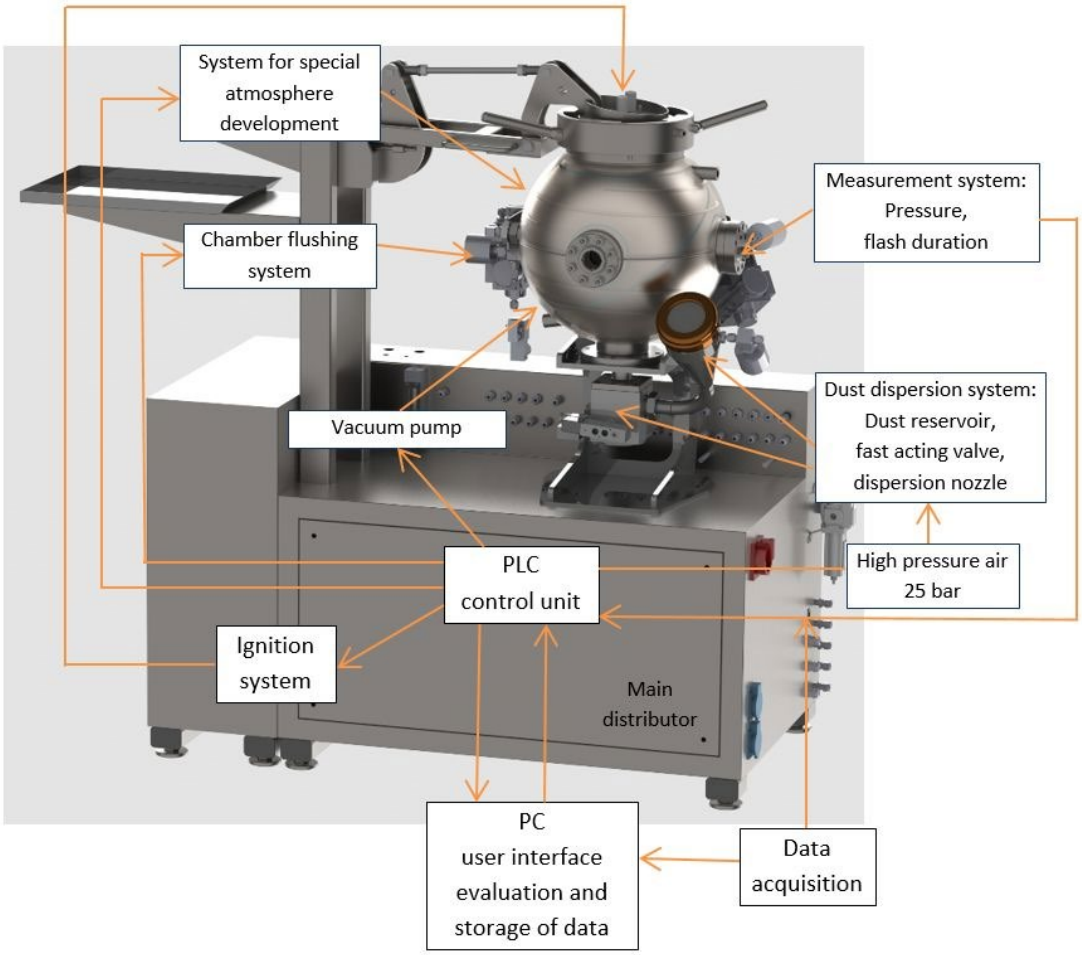

Figure 1: Test assembly

3. Calculation procedure

To reduce the number of experimental tests, preliminary thermodynamic and kinetic analyses were performed to predict the fuel-air equivalence ratio resulting in maximum pressure. Knowing the chemical equilibrium composition of a studied chemical system permits calculating theoretical thermodynamic properties for the system. In the calculation, we assume all gases to be ideal, and that interactions among phases may be neglected. The calculation procedure is based on the minimization of free energy and was successfully tested for the similar gas composition in Skřínský and Skřínská (2015). A calculation method of minimizing free Gibbs energy was used to quantify adiabatic explosion pressures at 15 different concentrations of the mixture and for three different initial temperatures. As input parameters, the kinetic mechanisms and thermodynamic data sets (C_p, S_0, H_0, G_0) were used primarily in the default THERMO.dat databases and Thermdat. tdd for GASEQ (GASEQ, 2005) in CHEMKIN standard polynomial format.

The Gibbs Free Energy G of the mixture at pressure p is given by:

$$\frac{G}{RT} = \sum_{i=1}^{nSp} \left(\frac{x_i G_i^0}{RT} + x_i \ln \frac{x_i}{\sum x_i} + x_i \ln p \right) \tag{1}$$

The results of adiabatic explosion pressure calculations, P_e, were used to predict the initial values for experimental biogas-air measurement in Figure 6 compared to measured experimental results.

4. Results and discussion

4.1 Pure gases

The maximum explosion pressure and maximum rate of pressure rise are essential indicators for the evaluation of explosion energy distribution. In the presented study, the measured maximum explosion pressure of stoichiometric methane-air is 7.3 bar, lower than the calculated adiabatic explosion pressure of 8.7 bar. This is attributed to the energy loss of the walls. The measured maximum explosion pressure of stoichiometric biogas–air is 4.1 bar, lower than the calculated adiabatic explosion pressure of 4.5 bar. Each test was repeated three times to obtain appropriately averaged results, and the average was plotted in the pressure-time curve. The maximum explosion pressures and maximum rate of pressure rise for pure gases, various equivalence ratios, and initial ambient conditions are presented in Figures 2-5.

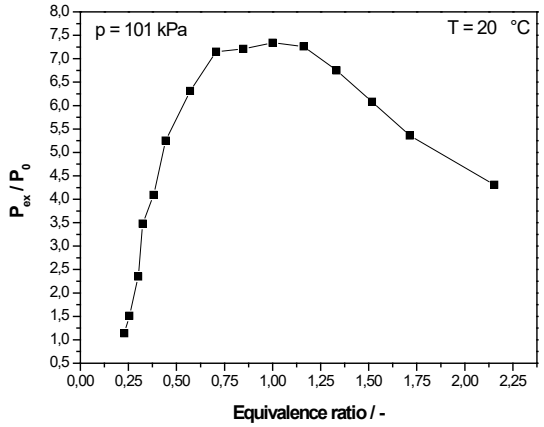

Figure 2: P_{ex}/P_0, versus equivalence ratio for CH_4

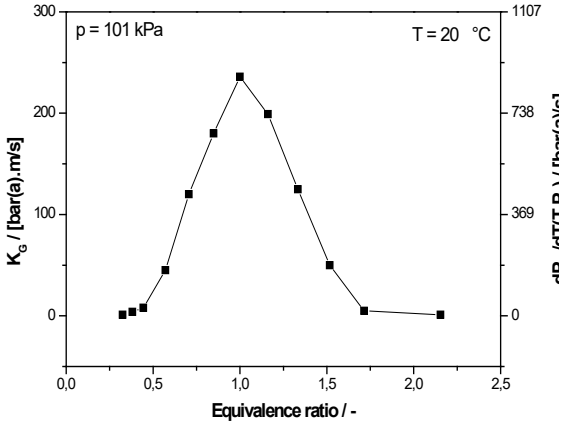

Figure 3: K_G versus equivalence ratio for CH_4

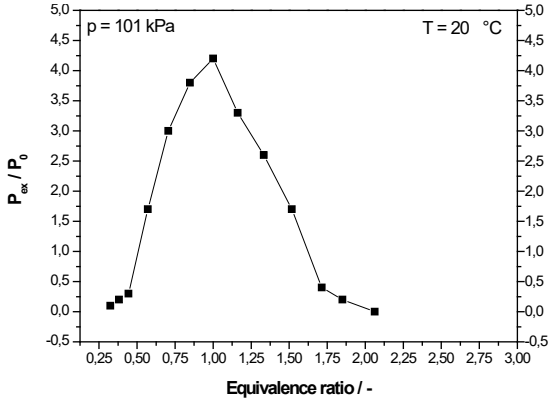

Figure 4: P_{ex}/P_0 versus equivalence ratio for Biogas

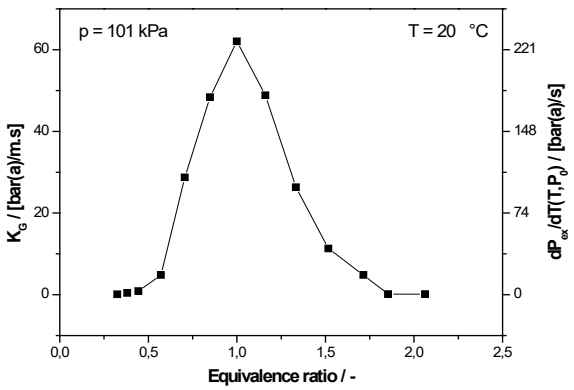

Figure 5: K_G versus equivalence ratio for Biogas

The fuel-air equivalence ratio was defined as:

$$\varphi = \frac{\left(\frac{\text{fuel}}{O_2}\right)}{\left(\frac{\text{fuel}}{O_2}\right)_{st}} \tag{2}$$

The deflagration index was defined as:

$$K_G = \left.\frac{dP}{dt}\right|_{max} \sqrt[3]{V} \tag{3}$$

4.2 Influence of the temperature

Figures 6-7 give different initial temperatures on the explosion pressure and the pressure rise rate during the explosion process. The explosion and adiabatic equilibrium pressure is normalized concerning the initial pressure (P_0 = 101 kPa).

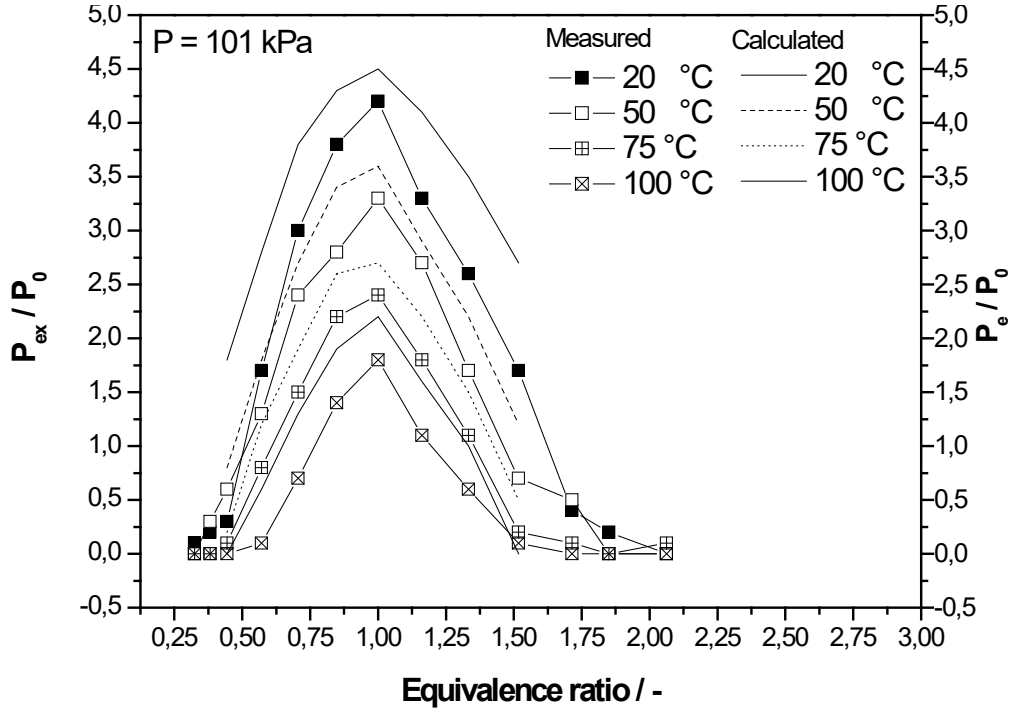

Figure 6: P_{ex}/P_0 versus equivalence ratio for Biogas

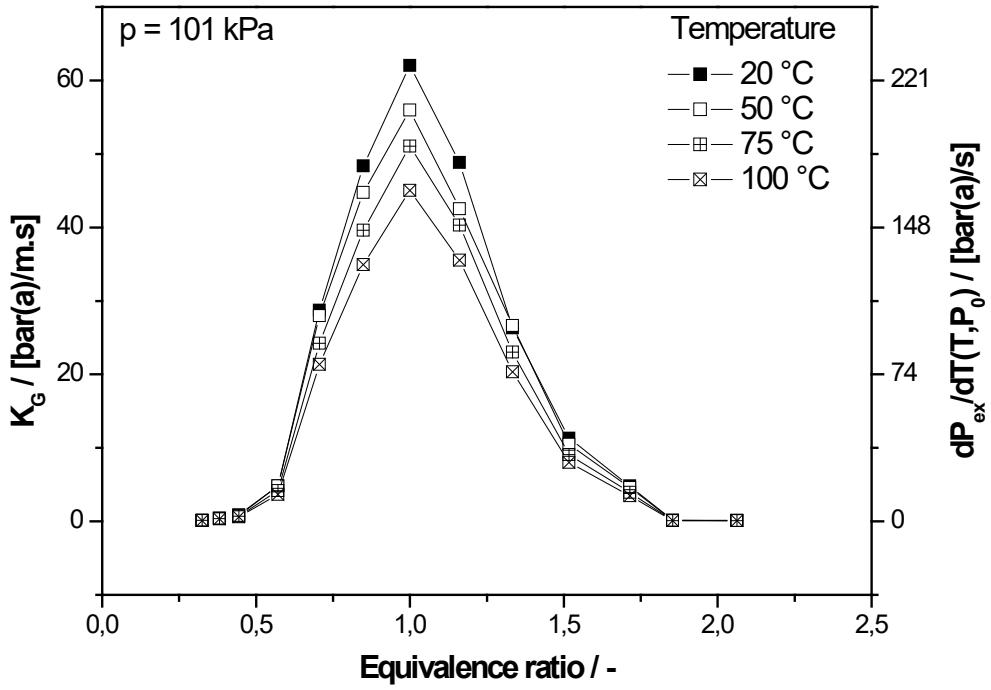

Figure 7: K_G versus equivalence ratio for Biogas

5. Conclusions

The explosion behavior of biogas-air mixtures with the representative real-scale composition of the gas ($CH_4/CO_2/O_2/H_2/H_2S$) was experimentally and numerically studied at the specific process and initial explosion conditions in a closed spherical explosion chamber situated at Energy Research Centre, VSB-TU Ostrava. An employed method combines the preliminary thermo-kinetic chemical equilibrium study to identify the specific equivalence ratios by further experimentally analyzing, thus substantially reducing the number of experimental tests. The presented results allow us to experimentally quantify the effect of different process temperatures on the pure gas-air explosion parameter – the maximum explosion pressure, the maximum rate of pressure rise, and the deflagration index. The biogas mixtures investigated can be classified based on the value of the deflagration index as low-reactivity mixtures. The highest weight of K_G found was 16 bar.m/s, which was much lower than the KG value of a pure methane-air combination that was 65 bar.m/s, both measured at ambient pressure and temperature. The main conclusions are summarized as follows:

1) Determination of maximum explosion pressure (P_{max}) and deflagration index (K_G) of biogas-air mixtures at temperatures of T = 20 - 100 °C and φ = 0.25 - 2.40 equivalence ratios.
2) Explosion pressure, rate of explosion pressure rise, and deflagration index of the biogas-air mixture reach maximum values near the stoichiometric concentration with an equivalent ratio Φ = 1.03 within the studied range, i.e., 0.25 - 2.40 at temperatures of 20 - 100 °C.
3) The explosion pressure varied between 4.2 to 1.8 bars, the rate of explosion pressure rise 60 to 45, and the deflagration index 16 to 12 bar. m/s for initial temperatures 20°C to 150 °C.

Nomenclature

G – Gibbs Free Energy, J/kg
K_G – deflagration index, bar.m/s
n_{sp} – number of species, -
p – pressure, N/m^2
R – universal gas constant, J/K.mol
st – stoichiometric conditions, -
t – time, s
φ – fuel-air equivalence ratio, -
T – temperature, K
V – vessel volume, m^3
x – number of moles in the mixture, mol

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