Experimental Research On The Biogas – Oxygen Mixture Detonation Cell Size

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1 Introduction

Humanity needs more and more energy. It is direly needed for both achieving economic development and improving standards of living across the planet. It is well known that living standards are high in countries with high industrial output and intense energy use. However, most of it is obtained from fossil fuels (coal, oil and natural gas) [1]. At the same time, climate change is more likely than not a fact and as such it causes a lot of concerns among the international scientific community and governments for a number of years now. As a result there is a growing research effort in the field of alternative and renewable fuels and energy production with low or no impact on the environment. Additionally it is also driven by regulatory and signing climate policies, like the newest Katowice Climate Package [2], by the members of the United Nations Framework Conventions on Climate Change (UN FCCC).

In the field of alternative fuels biogas is seen as a promising one for a number of reasons. The most important is that as it is produced from biomass, the net balance of CO_2 emitted into the atmosphere is close to 0. Moreover it can also be produced from bio-waste what is even more cost-effective [3]. Additionally, due to its storability it is a more reliable and stable energy source than weather dependent solar and wind [1].

Nevertheless, despite its advantages, biogas has some drawbacks. Low Lower Heating Value (LHV) compared to the natural gas or pure methane [4,5] is the biggest one. Low LHV means that an increased fuel flow in a turbine powered by biogas is required to maintain efficiency at an acceptable level [6]. This in turn leads to a decrease of the compressor surge margin [6–8] and overheating of the turbine blades [8,9] consequently shortening their useful life. To overcome those problems a detonative instead of the deflagrative combustion mode can be used.

The main advantage of the detonation combustion is the fact that it provides higher thermal efficiency when compared to the isobaric or isochoric cycle [7,8]. It can also take place in a wide variety of equivalence ratios from lean through stoichiometric to rich mixtures [9–11]. Burning a lean mixture has the advantage of lower flame temperature [8], which could solve the aforementioned problem of the turbine overheating. It was also shown that, especially for lean mixtures, detonation engines will have significantly lower NOx emissions [9] which in connection with low emission from biogas [6] is very promising.

Surprisingly, there is a very limited number of studies that dealt with biogas detonation and even less that researched the biogas detonation cell size. Most of them were done in Malaysia at the University of Technology and concerned fueling a Pulsed Detonation Engine with biogas. Wahid et al. [12] conducted experimental research with synthetic biogas consisting of 65% CH_4 and 35% CO_2 mixed with oxygen and diluted at various percentages with N_2. They showed that the detonation cell size increases as percent of N_2 in the mixture increases. Dairobi et al. [13] provided a general feasibility study of fueling the PDE with biogas. While in 2020 Elhawary et al. [14] reported an experimental study of PDE fueled by biogas with hydrogen enrichment and O_2 as an oxidizer. They investigated the influence of H_2 addition on the detonation cell size together with other detonation characteristics.

Notwithstanding the fact that burning biogas in detonative mode is a very encouraging direction there is minimal research in this area. The authors of this paper are strongly convinced that it should be investigated more deeply. In the presented work the authors report the results of experimental research on the detonation cell size of biogas. A wide range of compositions, equivalence ratios and initial pressures has been covered in the effort to provide a comprehensive description of the influence of those parameters on the detonation cell size. The authors also argue that due to the unstable cellular structure of the detonation, it is insufficient to report only the average cell size. Instead, the researchers propose a more detailed statistical description including at least standard deviation and the range of measured values.

2 Experimental setup

Figure. 1 presents the scheme of the experimental setup. The main element of the test stand was a stainless steel detonation tube with an inner diameter of 122.2 mm. On one end of the tube, an initiator filled with the hydrogen-oxygen stoichiometric mixture was placed. The pressure in the initiator ranged from 3 to 4 bar depending on the initial pressure of the biogas in the main tube. A foil diaphragm separated the initiator from the rest of the tube. The main (driven) section consisted of two two-meter-long segments with seven slots for pressure transducers and one for the temperature sensor. The purpose of this section was to stabilize the detonation wave passing from hydrogen-oxygen to the biogas-oxygen mixture. The test and dumping sections were placed downstream of the driven section. They were separated by a foil membrane. The purpose of the dumping section was to prevent the reflected shockwave from blowing out the recorded detonation cell pattern by attenuating the detonation wave.

The cellular structure of the detonation was recorded on the smoked foils cut from 0.5 mm aluminum sheets. They were covered with soot from a mixture of paraffin oil and toluene and carefully inserted into the test section before each experiment. During the experiment, propagating detonation left a cellular pattern visible on the foil. After the experiment, the foil was carefully removed and photographed using a camera. To allow correct measurements of the cells a paper scale was placed on the foil while taking the picture. The detonation cell size distribution was then obtained by marking the width of all recognizable and visible cells using AutoCAD software. The lengths of the drawn lines were then exported from AutoCAD and scaled using the aforementioned paper scale.

In this study a range of different equivalence ratios, initial pressures and compositions of the biogas were tested. The researched compositions of the biogas were: {70-30; 65-35; 60-40; 55-45; 50-50}, the first number represents the volume percentage of methane and the second number represents the percentage of carbon dioxide in the biogas. This means that for example the 70-30 mixture should be understood as 70% CH_4 + 30% CO_2 + O_2. The ranges of tested equivalence ratios and initial pressures (in bars) were {0.50; 0.75; 1.00; 1.25; 1.50} and {0.6; 0.7; 0.8; 0.9; 1.0; 1.2; 1.4; 1.6}, respectively.

Each mixture was prepared in a gas cylinder using the partial pressures method at least 24 hours before the experiment to ensure homogeneity. The pressure of the mixture in the cylinder was always set to 10 bar abs. Prior to the experiment, the mixture was fed into the detonation tube to the desired pressure and left for 2 minutes to stabilize.

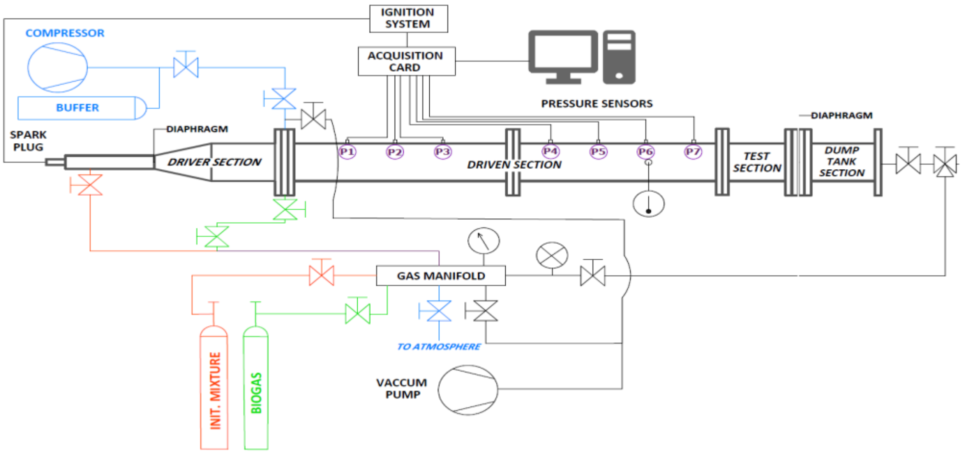

Figure 1 Schematic of the experimental setup.

3 Results

In this extended abstract its authors would like to shortly present exemplary results for a 70% CH_4 + 30% CO_2 + O_2 biogas. Figure 2 presents a comparison between an average detonation velocity calculated using the velocities between pressure transducers P4-P5, P5-P6 and P6-P7 and the theoretical Chapman-Jouguet detonation velocities calculated for presented cases. The whole range of pressures and equivalence ratios used in experiments is covered in this chart. It can be easily seen that the detonation velocity increases with the increasing pressure and equivalence ratio. It is also evident that the results were in good agreement with a theoretical values as almost all of them fall withing 2% margin shown.

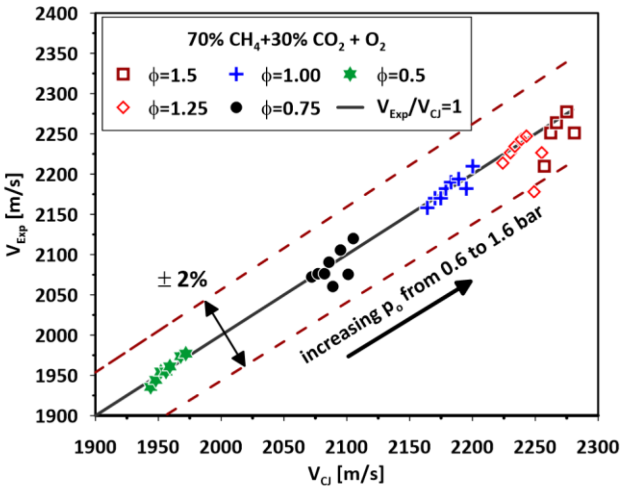

Figure 2 Average detonation velocity from all the 70-30 cases compared to theoretical Chapman-Jouguet detonation velocity V_{CJ}.

The main result expected from the experiments was to record the cellular structure of the detonation wave on the sooted foil. The detonation cell size depends mainly on the initial pressure, equivalence ratio and mixture composition. For the presented case it ranged from around 2 mm up to 40 mm. Figures 3a and 3b present an average cell size as a function of equivalence ratio Φ and initial pressure p_0, respectively. In the Figure 3a one can see that when the initial pressure is kept constant the smallest cell sizes are found for Φ = 1 and they increase when the value of equivalence ratio move away from 1. At the same time, in the Figure 3b it can be seen that when the equivalence ratio is fixed and the initial pressure increases the cell size decreases.

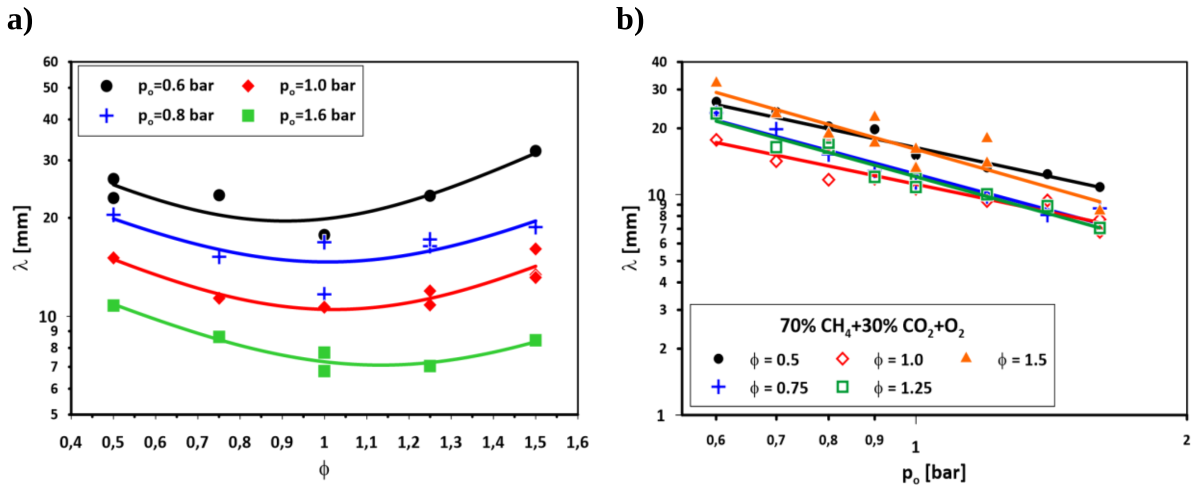

Figure 3 Average **c**ell size dependence on: a) equivalence ratio Φ; b) initial pressure p_0. Continuous lines represent fitted power and polynomial function, respectively in a) and b) while symbols represent experimental results

The distribution of the data from the case of Φ = 1.25 is presented below. Figure 4 presents the box and whiskers plot. The box shows the interquartile range while the horizontal line inside it shows the mean value of the detonation cell size in each of presented case. At the same time the whiskers mark the maximum and minimum measured detonation cell values. Additionally, Table 1 presents statistical description of the presented data. From Figure 4 it appears that cell size variation is increasing as initial pressure decreases. However, it can be also observed that the spread of measured values and the mean are always of the same order of magnitude. What is more, calculated value of the coefficient of variation (CV) always oscillates around 0.19. The CV is defined as the ratio of the standard deviation to the mean, it is a standardized measure of dispersion showing the extend of variability in relation to the mean. The average value of CV from all experiments of the presented case was 0.191 with standard deviation equal to 0.027, meaning that the relative variation of the cell size stays roughly the same throughout the

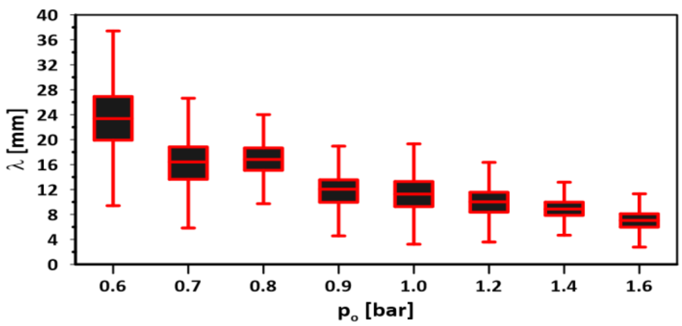

Figure 4 Histograms showing the data distribution of experimental results for a 70-30 case of equivalence ratio Φ = 1.25.

experiments. This leads the authors to believe that the observed increase in variation is not caused by any kind of methodological error or interaction between experiment’s parameters.

Table 1 Statistical description of the equivalence ratio Φ = 1.25 case presented in Figure 6.

p_0 [bar]	N	Min	Max	Spread	Mean	Std	Var	CV
0.6	89	13.17	33.41	20.24	23.38	4.95	24.53	0.21
0.7	201	10.43	24.14	13.71	16.43	3.47	12.02	0.21
0.8	119	11.43	21.87	10.44	16.82	2.45	6.00	0.15
0.9	104	8.26	18.62	10.3	12.06	2.63	6.93	0.22
1.0	160	7.35	17.10	9.75	11.26	2.22	4.91	0.20
1.2	445	6.30	14.35	8.05	10.03	2.02	4.07	0.20
1.4	321	6.12	12.08	5.96	8.87	1.43	2.03	0.16
1.6	369	4.63	10.20	5.57	7.05	1.40	1.95	0.20

4 Discussion and summary

During the research a considerable variability in the detonation cell size for each case was encountered. This was an effect of a very unstable cellular structure that was observed on the sooted foils obtained from the experiment. The detonation wave structure strongly resembled the irregular cell shapes presented by Ng [15] and Pintgen et al. [16]. Due to this fact the authors concluded that providing only an average value of measured detonation cell is insufficient and decided that a more comprehensive statistical description should be provided. Consequently, the authors postulate that it should be always provided when reporting experimentally obtained cell sizes especially for mixtures with a very unstable cellular structure. This is very important in the context of possible future design efforts regarding engines like PDE or RDE, especially that those engines will most likely use air a not oxygen. This means that the presence of nitrogen in the air will render the cellular structure even more unstable [16].

In this conference abstract an exemplary results of experimental detonation cell measurements for a 70% CH4 + 30% CO2 + O2 mixture are presented. It is shown that the cell size λ depends both on the initial pressure and the equivalence ratio Φ. The presented analysis was also conducted for all the other mixtures mentioned at the beginning of this abstract and will be showed during the conference. Additionally, it also argued that due to the very unstable cellular structure of the detonation wave it is insufficient to provide only an average value of the measured detonation cell size. Hence, more detailed statistical description is provided with hope to introduce it as a standard when reporting detonation cell size measurements, especially for mixtures with unstable structure.

5 References

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