The Influence of the Initial Temperature on DDT Characteristics in a Valveless PDC

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Abstract The detonation velocity and the detonation cell width are determined experimentally as a function of the initial mixing temperature in a valveless pulse detonation combustor (PDC). The initial temperature was varied from 290 K up to 650 K. To shorten the run-up distance to the deflagration-to-detonation transition (DDT), the detonation tube was equipped with six orifice plates which support the flame acceleration. Ionization probes are used to record the combustion event at several axial positions. Sooted foils inside the downstream section of the detonation tube are used to record the imprint of the detonation front and to determine the detonation cell width. It was found that the propagation speed of the detonation front decreases with increasing mixing temperature, which agrees with the theoretical temperature dependence of the CJ-velocity. The detonation cell width decreases linearly for elevated initial temperatures.

Keywords PDC · Detonation tube · Detonation cell width · Detonation velocity
Temperature variation · Flame acceleration

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1 Introduction

Pressure gain combustion is a promising way of achieving a remarkable increase in the thermal efficiency of gas turbines [1]. Although there are several approaches of realizing an approximate constant volume combustion (aCVC), e.g., wave rotor [2], shockless explosion combustor (SEC) [3], and rotational detonation combustor (RDC) [4], the pulse detonation combustor (PDC) [5] is the most investigated design. Nevertheless, the design of a reliable and efficient PDC is not a straightforward task. Many parameters have a notable influence on the behavior of a PDC, among them are the detonability of the mixture, the detonation cell width, the initial conditions, and the geometry.

The effect of the initial temperature on the deflagration-to-detonation transition (DDT) is one of the least studied aspects. Only few and partially contradictory experimental and numerical data related to this topic have been published. As a characteristic length scale of a detonation wave, the detonation cell width λ is a meaningful parameter when predicting the operation of a PDC. However, the influence of the temperature of hydrogen–air mixtures on the cell width is only rarely investigated. Ciccarelli et al. [6] found that the cell width for a stoichiometric mixture decreases from $\lambda \approx 9$ mm to $\lambda \approx 5$ mm by increasing the initial temperature from $T = 300$ K to $T = 650$ K at a constant initial pressure of 1 bar. However, no data was found for initial temperatures in between the named temperature range. A one-dimensional numerical study, performed by Djordjevic et al. [7] suggests a non-linear dependence in which detonation cell width takes on a minimum value for an initial mixing temperature of about 320 K. For a further increase in temperature, the cell width calculated by Djordjevic et al. increases. As shown in [7], these contradicting results regarding the dependence of the cell width on the initial temperature are caused by two competing effects of increased initial temperature. The post-shock temperature rises while the von-Neumann pressure decreases due to the increased speed of sound in the unburned mixture causing a decrease in the Mach number of the detonation wave. The influence of these state variables on the cell width is still not fully understood and so the influence of the temperature on the resulting detonation cell width cannot be predicted with certainty.

Due to the few available data and the difficulty of prediction, the detonation velocity and the detonation cell width are determined in this work for an initial temperature from 290 K to 760 K. The measurements are carried out in a valveless PDC test rig that is run in single-cycle operation, using it effectively as a single shot detonation tube. Thermocouples and ionization probes are used to identify the initial temperature and the propagation speed of the detonation front, respectively. Sooted foils are used to record the imprint of the triple points of the detonation wave and to determine the detonation cell width.

2 Experimental Setup

2.1 PDC Test Rig

A valveless PDC (Fig. 1) has been designed to enable a wide spectrum of investigations on pulse detonation combustion.

The detonation tube has a total length of $L = 2.2$ m and an inner diameter of $D = 40$ mm. The main air flow is sent through the preheater, where it can be heated up to 1100 K. The air mass flow is set to a constant value of 80 kg/h using a closed-loop control including a Coriolis mass flow meter (Endress+Hauser Proline Promass 83 F) and an electronic control valve (Bürkert 8630). Due to disturbances in the supply and the inertance of the control, there is a fluctuation of the air mass flow of ± 5 kg/h. Four solenoid valves (Bosch 0 280 158 827) are used for the control of the fuel mass flow, which was measured by a Coriolis mass flow meter (Endress + Hauser Cubemass DCI). The pressure upstream of the solenoid valves is set manually in order to match the mass flow of 2.34 kg/h when all valves were open, which corresponds to an equivalence ratio of $\Phi = 1$. The measurement error of the fuel mass flow due to the accuracy of the Coriolis mass flow meter and pressure fluctuations in the supply line is assumed to be ± 0.05 kg/h. These uncertainties in the mass flow of air and fuel result in an actual equivalence ratio of $0.91 < \Phi < 1.09$. Ciccarelli et al. [6] and Djordjevic et al. [7] independently found that the deviation of the cell width over this range of Φ is negligible. Due to this, the results are expected to represent the dependence of the detonation cell width on the initial temperature reliably. The applied mass flow rates result in a filling of the entire detonation tube in about 100 ms. Nevertheless, the solenoid valves are opened for 2 s before the mixture is ignited. When the solenoid valves are opened, the supply pressure drops until it stabilizes at a certain level. This pressure level is a function of the geometry of the supply line and the installed components. The variation of the upstream pressure induces a change in the pressure drop along the valves, resulting in an unsteady fuel mass flow. The filling time of 2 s is chosen to minimize the transient effects during the initial phase after opening the valves on the mixture in the detonation tube right before ignition.

Two pressure transmitters (FESTO SPTW) were used to record the static pressure in the fuel line upstream and downstream of the solenoid valves. The measured data confirm a constant pressure gradient during the last 500 ms of the filling process, which ensures a constant fuel mass flow over this time span and so induces

Fig. 1 Sketch of the PDC test rig with thermocouples T_1 and T_2 and ionization probes I_1 – I_4

Fig. 2 Detailed view of the inlet geometry of the PDC test rig

a homogeneous equivalence ratio along the tube. The mixture is ignited using an automotive spark plug that initiates a deflagration that travels downstream. Orifice plates with a blockage ratio of 0.43 lead to an acceleration of the flame and enhance DDT. The chosen obstacles and separation distances were found to be a favorable geometry for efficient flame acceleration by Gray et al. [9].

A detailed view of the inlet section of the PDC test rig is shown in Fig. 2. The inlet of the combustion tube is formed by a hemispherical wave reflector that was designed as a fluidic diode. During the filling process, the gas enters the combustion tube with a small pressure loss. After the ignition event, the wave reflector impedes the hot gas from traveling upstream and supports the flame acceleration due to its high pressure loss coefficient in the upstream direction. The spark plug is located at the center of the hemisphere.

2.2 Measurement Methods

2.2.1 Temperature Measurement

Thermocouples are used to measure the temperature downstream of the wave reflector (T_1) and inside of the exhaust tube (T_2) next to the sooted foil (Fig. 1). Sheathed thermocouples of type K with a diameter of 3 mm were chosen to ensure the robustness of the sensors when exposed to detonation waves. The applied setup includes a measurement error of ± 3 K. The recorded output signals allow for determining the mixing temperature immediately before the ignition event. One could expect a large decrease in the measured temperature due to the injection of hydrogen at ambient temperature. For example, the Riemann mixing rule supposes a temperature drop of about 90 K for an initial temperature of 600 K. However, the measured temperature only decreases by about 5 K when injecting hydrogen. This discrepancy is likely to arise from heating of the mixture by hot walls, which is supported by the fact that the associated temperature drop at T_2 is lower than at T_1 .

2.2.2 Ionization Probes

Ionization probes are used to detect the flame front at four axial positions in the combustion tube: two probes inside the flame acceleration section and two probes in the exhaust tube (Fig. 1). The axial positions of the probes relative to the spark plug are listed in Table 1.

Figure 3 shows a typical output signal of the four ionization probes. The variation from the voltage output is plotted over time: When the flame front passes an ionization probe, its voltage output decreases as a result of the increased conductivity of the gas. Since the ionization probes I_1 and I_2 detect a deflagration while the probes I_3 and I_4 detect a detonation wave, the output signal differs remarkably between the two pairs of probes. The deflagration wave causes a small decrease in the voltage that lasts for more than 1 ms. In the exhaust tube, the detonation wave provokes a sharp decrease in the voltage of the probes I_3 and I_4 . Additionally, the voltage recovers already after about 0.2 ms.

2.2.3 Sooted Foils

The cellular structure of the detonation wave is recorded by a sooted foil, which is inserted into the rear part of the combustion tube. For this purpose, precision spring steel is cut to pieces of $100 \text{ mm} \times 600 \text{ mm}$, which are sooted by a fuel-rich diffusion flame of acetylene in air. Subsequently, the foil is rolled up lengthwise and inserted

Table 1 Axial positions of ionization probes

Ionization probe I_i	I_1	I_2	I_3	I_4
Axial position x_i (mm)	180	220	1050	1450

Fig. 3 Exemplary signal of the output voltage U of the ionization probes over time

into the downstream section of the combustion tube (Fig. 1). After a single detonation event in the PDC, the foil is removed from the test rig and the imprint is digitized. Image processing is used to optimize visibility of the detonation cell structure.

Hébral and Shepherd [10] developed a tool, which was applied in this work to determine the detonation cell width from the optimized photographs of the sooted foils. The output of the 2D-correlation tool consists of the size of the most dominant structures of the analyzed picture and the associated relative energies. The most dominant structure (i.e., the structure with the largest relative energy) is assumed to be the detonation cell width. Multiple pictures are extracted from each sooted foil, which are then evaluated separately. The dominant cell width for one foil is determined by averaging the results from the individual pictures weighted by their corresponding relative energy. This weight takes the quality of the picture into account, since a large relative energy suggests a reliable result. This correlates with the quality of the picture which is mainly defined by the contrast and the sharpness of the cellular structure.

3 Results and Discussion

3.1 Detonation Velocity

The time resolved output signals of the ionization probes are used to determine the time at which the detonation wave passes the probe. Considering the axial distance of the two probes in the exhaust tube of $x_4 - x_3 = 400$ mm, the propagation velocity of the detonation front v_{det} can be calculated using time-of-flight subtracting the flow velocity:

$$v_{\text{det}} = \frac{x_4 - x_3}{t_4 - t_3} - v_{\text{flow}}. \quad (1)$$

The flow velocity of the mixture can be expressed as a function of the mass flow rates $\dot{m}$ of air and fuel and the mixing temperature T_{mix} :

$$v_{\text{flow}} = \frac{T_{\text{mix}}}{pA} (\dot{m}_{\text{air}} R_{s,\text{air}} + \dot{m}_{\text{fuel}} R_{s,\text{fuel}}), \quad (2)$$

with the initial pressure p , the cross-section area of the detonation tube A and the specific gas constant R_s . This velocity is not negligible and can be as high as $v_{\text{flow}} = 55$ m/s in case of $T_{\text{mix}} = 760$ K. Figure 4 shows the measured propagation velocity of the detonation front over the initial temperature.

Since the velocity is calculated from the time instances t_3 and t_4 , at which the detonation wave passes the ionization probes 3 and 4 respectively, the accuracy of these time instances is of high importance for the error estimation. The voltage output of the probes is recorded with a sampling frequency of $f_s = 1$ MHz. Hence, the maximal accuracy for the determination of t_3 and t_4 is ± 1 μ s. Due to the detection

Fig. 4 Measured propagation velocity v_{det} of the detonation front over the initial mixing temperature T_{mix} compared to the CJ-velocity and the expected range of deviation due to uncertainties in the equivalence ratio at a constant initial pressure of 1 bar

of the time at which the reaction front passes the sensors, a measurement error of $\pm 2 \mu\text{s}$ results for $\Delta t = t_4 - t_3$. For an axial distance of $x_4 - x_3 = 0.4 \text{ m}$, this leads to an error of $\pm 20 \text{ m/s}$ in the range of the measured velocities.

Beside the measured propagation velocities, Fig. 4 shows the CJ-velocity for a perfect mixed fuel–air mixture with an equivalence ratio of $\Phi = 1$ and the expected range of measured data points taking the variation of the actual equivalence ratio and the measurement error of the velocity into account.

It can be seen that all the measured velocities are located in the expected range. The variance of the propagation at a certain temperature can be explained by the measurement error of the velocity by the ionization probes of $\pm 20 \text{ m/s}$. For temperatures between 400 K and 500 K the mean detonation velocity exceeds the CJ-velocity, which can be explained by a fuel mass flow that has been set slightly too high for these conditions. Nevertheless, every measured propagation velocity is located in the expected range, which implies that the mass flow rates have been adjusted correctly with the given precision.

3.2 Detonation Cell Width

Figure 5 shows the photographs of three different sooted foils. These foils have been generated at an initial temperature of 290 K, 500 K and 650 K respectively.

Three different types of appearance were found, each visible in one photograph in Fig. 5. For a temperature range of 290–380 K, the foils show a homogeneous distribution of the soot, which results in low contrast in the photographs. The detonation cells are indicated by thin, dark lines (Fig. 5a). The second type, which has been observed for a temperature between 450 and 550 K, is characterized by dark cells separated by thick lines where the soot has been removed by the movement of the triple points. An initial temperature of 600 K and more led to a fish-scale-like appearance of the detonation cell structure. While there is an abrupt change between the first and the

Fig. 5 Processed photographs of sooted foils at three different initial temperatures show various types of appearance of the cellular structure

second type, there is a smooth transition between the second and the third type, which causes a simultaneous appearance of the latter two types for a mixing temperature of 550 and 600 K.

The detonation cell width is determined from photographs of the sooted foils using a 2D-correlation tool developed by Hébral and Shepherd [10] as mentioned in Sect. 2.2. Since this tool has to be operated manually at some points, a random error appears. Due to the small contrast, the photographs of type 1 are the hardest to evaluate which increases the error of the calculated cell width considerably for the respective temperature range. To estimate the human error, the evaluation of the photographs have been performed by two different persons independently. It was found that the individual values might deviate up to 3 mm but the averaged cell width deviates only by a small margin. Figure 6 shows the measured detonation cell width λ over the initial temperature.

As described by Djordjevic et al. [7] the detonation cell width is affected by two opposing effects when the mixing temperature is increased. The speed of sound increases resulting in a lower Mach number of the detonation wave. Therefore, the von-Neumann pressure decreases while the post-shock temperature is increased. The resulting effect on the cell width is dependent on the mixture and the initial conditions. The performed experimental study of the detonation cell width in a stoichiometric hydrogen–air mixture as a function of the initial temperature at a constant initial pressure of 1 bar shows that the cell width decreases over the temperature.

Fig. 6 Detonation cell width λ over the initial mixing temperature T_{mix} , measured every 50 K at a constant initial pressure of 1 bar

The results from Djordjevic et al. are matched only for ambient temperature. For higher temperatures, the calculated cell widths are too large compared to the experimental results. This is most likely due to the fact that the calculations are based on the one-dimensional ZND detonation model, and thus, cannot cover the entirety of the complex shock interactions that take place in a real, multidimensional detonation front. As suggested by Gavrikov et al. [11], these interactions might play a decisive role in defining the initial conditions of the reactive mixture before the onset of combustion under certain circumstances: Due to additional compression by transverse shock waves and resulting shock collisions, the actual strength of the shock that causes the mixture to auto-ignite may exceed the one predicted by the von-Neumann state based on the ZND detonation model. As described before, since several post-shock parameters such as temperature, pressure and relative velocity all contribute to the formation of detonation cells, partly through opposing effects, the influence of multidimensionality should be considered to improve numerical agreement with experimental data.

The experimental results agree well with the investigations by Ciccarelli et al. [6], who observed a decrease from $\lambda(300 \text{ K}) \approx 9 \text{ mm}$ to $\lambda(650 \text{ K}) \approx 5 \text{ mm}$ for atmospheric initial pressure conditions. The measurement results suggest slightly larger values for both temperatures which can be explained by uncertainties in the determination of the cell width. Furthermore, a linear dependency of λ and T was observed in this work for the entire temperature range which exceeds the previously investigated temperature spectrum.

3.3 Initial Flame Acceleration

The ionization probes I_1 and I_2 are used to record the flame velocity between the first and the second orifice plate. As described by Smirnov and Nikitin [8], the detonation run-up distance is strongly dependent on the initial flame acceleration. Hence, the velocity of the deflagration front in the beginning of the combustion tube is a relevant parameter for characterizing the DDT in the valveless PDC used in this work. The coupling criterion implies that the flame propagation speed has to exceed the speed of sound of the unburned mixture before DDT can take place. Thus, the Mach number of the deflagration wave M_{defl} is a good indicator for the magnitude of the DDT run-up distance. Figure 7 shows the Mach number of the flame between the first two ionization probes relative to the unburned mixture. The speed of sound for the stoichiometric mixture of hydrogen and air has been calculated as proposed by Vrkljan [12].

Up to a temperature of $T \approx 400$ K, the Mach number decreases significantly. In this regime, the decrease in density apparently has a larger effect on the reactivity than the increase in temperature. When further increasing the temperature, the Mach number of the flame front stays at a constant level of $M \approx 0.3$ which implies the further decrease in the density of the mixture is compensated by the rise in temperature. This relation between mixing temperature and initial flame acceleration implies an increase of the DDT length for a rise in temperature up to 400 K for the used geometry setup. For further increase in temperature, the DDT-length is assumed to be independent of the mixing temperature which is a useful characteristic when designing a PDC for integration in a gas turbine.

Fig. 7 Mach number of the deflagration wave relative to the unburned mixture M_{defl} between ionization probes I_1 and I_2 over the initial mixing temperature T_{mix} at a constant initial pressure of 1 bar

4 Conclusion

Detonation properties are strongly dependent on the mixture and the test rig geometry. A valveless PDC test rig has been used to record data for stoichiometric hydrogen–air mixtures for a temperature variation from 290 K to 620 K. The detonation cell width has been determined experimentally using sooted foils and digital data post-processing.

It was found that the cell width decreases linearly by increasing the temperature. The measured cell widths for ambient temperature and for $T = 650$ K are in good agreement with the available literature. Additionally, the initial flame velocity and the detonation velocity have been determined from the time-resolved output signal of four ionization probes at different axial positions. For temperatures less than 400 K, the flame acceleration is influenced mainly by the density decrease, leading to a decreasing Mach number of the flame with increasing mixing temperature. For higher temperatures, this effect is nullified by the increase in the initial temperature which leads to an almost constant Mach number of the flame relative to the unburned gas. As mentioned above, the DDT run-up distance is assumed to follow the dependency between the mixing temperature and the initial Mach number, which must be verified in future investigations. When designing a PDC for application in a gas turbine, the knowledge of the influence of the mixing temperature on the detonation cell width and, thus, the detonability of the mixture is crucial to optimize the robustness as well as the efficiency of the system.

The accurate control of the equivalence ratio is a major task when realizing reproducible series of measurement in a detonation tube. When running the PDC at multi-cycle operation, this becomes even more challenging due to unsteady states in the air and fuel supply lines. To ensure reproducibility, it is planned to develop a concept to measure and to control the fuel mass flow at multi-cycle operation.

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