Detonation initiation by shock focusing at elevated pressure conditions in a pulse detonation combustor

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Abstract
This work contains experimental investigations on the correlation of the detonation initiation process via a shock-focusing device with various initial pressures and mass flow rates. A pulse detonation combustor is operated with stoichiometric hydrogen–air–oxygen mixtures in single cycle operation. A rotationally symmetric shock-focusing geometry evokes the onset of a detonation by the focusing of the reflected leading shock wave, while a blockage plate at the rear end of the test rig is applied to induce an elevated initial pressure. The results show that the reactivity has a major influence on the success rate of detonation initiation. However, measurements with different blockage plates suggest that the mass flow rate has to be considered as well when predicting the success rate. Three main statements can be drawn from the results. (1) An increase in the mean flow velocity induces higher velocity fluctuations which result in a stronger leading shock ahead of the accelerating deflagration front. (2) An increase in the initial static pressure reduces the critical shock strength that must be exceeded to ensure successful detonation initiation by shock focusing. (3) Since the initial pressure is directly linked to the mass flow rate, these contrary trends can cancel each other out, which could be observed for 40% vol. of oxygen in the oxidizer. High-speed images were taken, which confirm that the detonation is initiated in the center of the converging–diverging nozzle due to focusing of the leading shock.

Keywords
Pulse detonation combustion, shock focusing, deflagration-to-detonation transition, elevated pressure

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1 Introduction
Increasing the thermal efficiency of the gas turbine cycle is a major challenge in energy generation. However, only small step improvements, due to physical limits, have been made in the last decades. This stagnation could be overcome by the implementation of a pressure gain combustion (PGC) process. The resulting thermodynamic cycle promises a substantial gain in thermal efficiency compared to the conventional Brayton cycle.1

Pulse detonation combustors (PDCs) are a promising concept for realizing PGC. Nevertheless, the efficient and reliable initiation of a detonation is challenging and has been investigated extensively in the past. Direct detonation initiation demands a high-energy deposition which cannot be provided by conventional ignition sources.2 The process of deflagration-to-detonation transition (DDT) allows for detonation initiation using a far lower application of energy. In order to realize an efficient PDC process, a reliable DDT with a short run-up distance is vital. Experiments on DDT in rough tubes have been conducted by Shchelkin,3 which led to the development of the Shchelkin spiral, a helical structure that increases turbulence close to the tube wall, and thus, promotes DDT. Lee et al.4 compared the effect of a Shchelkin spiral and a series of orifice plates on detonation
initiation. Further investigations on obstacle filled tubes have been conducted by Bychkov et al., Ma et al., and others. Silvestrini et al. empirically found that an increase in blockage ratio leads to a decrease of the run-up distance. Comparable results were found by New et al. who stated that convenient decrease in DDT run-up distance by the use of a Shchelkin spiral could only be observed for spirals with a large blockage ratio. Although reliable DDT could be achieved, the substantial loss in total pressure represents a main drawback of obstacle filled DDT geometries. Other groups achieved reliable PDC operation with a short DDT length using plasma-assisted detonation initiation or the application of a pre-detonator.

Focusing a shock wave using a single obstacle can also lead to detonation initiation, while inducing considerably smaller pressure loss than using a series of orifice plates or a Shchelkin spiral. This shock-to-detonation transition (SDT) was first investigated by Frolov et al. for propane–air mixtures and natural gas–air mixtures. The shock wave in these investigations was generated via a bursting diaphragm. Semenov et al. showed that sinusoidal conic expansion can lead to detonation initiation close to wall for failure of SDT inside the nozzle. When a suitably reactive gaseous mixture (e.g. hydrogen–air) is used, a sufficiently strong shock can be generated only by means of the flame, eliminating the need for a bursting diaphragm and allowing for continuous cyclical operation. Due to the closed ignition end of the PDC, the expansion of the burned gas leads to an acceleration of the flame front. Pressure waves are generated that induce a velocity in the unburned mixture while simultaneously increasing the pressure and temperature ahead of the flame, which supports the flame acceleration. The pressure waves accumulate ahead of the flame front to form a leading shock wave. Gray et al. successfully used a converging–diverging nozzle for detonation initiation in a PDC by focusing this leading shock ahead of the deflagration front.

Dorofeev et al. supposed that the DDT run-up distance mainly depends on the reactivity of the mixture which is closely linked to the detonation cell width. Based on this, Gray et al. used oxygen-enriched air as oxidizer in an atmospheric PDC test rig in order to match the cell width of a stoichiometric hydrogen–air mixture at the conditions of a micro gas turbine (3bar, 400 K). Numerical simulations by Bengoechea et al. indicated an almost deterministic DDT by shock focusing. Considering the rather stochastic behavior of detonation initiation reported by Schultz et al. using a Shchelkin spiral and the earlier mentioned pressure loss, the application of a shock-focusing geometry should be preferred for gas turbine integration of a PDC. However, the interaction of the formation and the focusing of the leading shock inside a PDC with varying initial pressure and Reynolds number have not yet been investigated.

The scope of this work includes experimental investigations of two processes that can be observed in the PDC test rig operated with stoichiometric hydrogen–oxygen–nitrogen mixtures: (1) the formation of a leading shock ahead of the deflagration in the pre-detonation chamber that is formed by compression waves due to the closed end wall and expansion of the burned gas and (2) the detonation initiation via focusing of the leading shock inside the converging–diverging nozzle. In order to gain a solid understanding of the relevant parameters, the flow rate and the initial pressure are varied. The amplitude of the leading shock of the deflagration front is examined as well as the detonation initiation success rate. In addition, high-speed images of the detonation initiation inside the shock-focusing geometry were taken.

2 Experimental setup

A PDC test rig for elevated initial pressure conditions has been designed and set up at the Chair of Fluid Dynamics at TU Berlin. For the present experiments, the test rig has been equipped with a converging–diverging nozzle for detonation initiation by shock focusing. The test rig, sketched in Figure 1, consists of a pre-detonation chamber ($L = 364$ mm, $D = 40$ mm),

![Figure 1. Schematic of the PDC test rig with a shock-focusing nozzle, continuous oxidizer flow and pulsed fuel injection. Orifice plate at the exhaust allows for initial pressure variations. Sensors for static pressure (F), dynamic pressure (P), and temperature (T) are installed at various locations.](image-url)
a converging-diverging nozzle with a minimum diameter of 20mm, and a detonation tube \( L = 1 \text{ m}, D = 30 \text{ mm} \). The valveless inlet design provides a constant mass flow of oxidizer. The fuel is injected into the mixing geometry via six solenoid valves (Bosch 0280158827). A dome-loaded pressure regulator (Swagelok RD6) is used to control the stagnation pressure in front of the valves in order to adjust the fuel mass flow. In this work, hydrogen is used as fuel due to its potential as an environmentally friendly alternative to hydrocarbon fuels. In addition, hydrogen is very reactive, and thus, is a promising fuel for PDC application. The premixed gas is then guided through three injection tubes that lead to three azimuthal injection ports close to the planar end wall of the PDC. A spark plug in the center of the flat end wall is used for ignition after filling the PDC with a flammable mixture. The flame then propagates downstream in the pre-detonation chamber, while pressure waves are generated by the unsteady heat release of the flame as well as by the expansion of the burned gas. Under the correct conditions, the focusing of the leading shock by the converging-diverging nozzle leads to initiation of a detonation which propagates downstream. An orifice plate is applied to create an outlet blockage. This results in an additional pressure loss at the rear end of the PDC leading to an elevated initial pressure.

In order to increase the reactivity of the mixture, oxygen-enriched air is used as oxidizer. The mass flow rates of air and oxygen are controlled separately by two electric proportional valves (Bürkert 2712) and measured via two individual Coriolis mass flow meters (Endress+Hauser Promass 80A and 83F respectively). The two mass flow rates are used for controlling the concentration of oxygen in the oxidizer and the flow velocity. Oxygen concentrations between 21 and 40% vol. were investigated.

A thin-film metal pressure sensor \( F_N \) (Festo SPTW) is installed 33mm upstream of the shock-focusing geometry for static pressure measurements. The initial pressure of each measurement is provided by the evaluation of the sensor information during the filling of the PDC. Additionally, two pressure sensors \( F_R \) and \( F_O \) of the same type are installed to monitor the fuel and oxidizer supply pressure. At the same time, a coated thermocouple \( T \) (Type K) provides the initial temperature of the reactive mixture.

### 2.1 Measurement procedure

The operating frequency was set to 0.5 Hz. This ensures independent single shots with comparable initial conditions, since pressure fluctuations were found to decay within 500 ms. The initial temperature and static pressures are verified for each measurement by a thermocouple \( T \) and a static pressure sensor \( F_N \).

Preliminary experiments with an injection time of \( \Delta t_{\text{inj}} = 5.5 \text{ s} \) provide data for mapping the measured fuel supply pressure upstream of the mixing geometry \( F_F \) to the fuel mass flow rate. The long injection time allows for an accurate measurement of the fuel mass flow rate by a Coriolis mass flow meter (Endress+Hauser Cubemass DCI). The injection time of \( \Delta t_{\text{inj}} = 0.5 \text{ s} \), which is used for all measurements of the present work, does not allow for the usage of the Coriolis mass flow meter. However, the preliminary data combined with the known number of open fuel valves allow derivation of the fuel mass flow rates. Due to the continuous flow of oxidizer, the mass flow rates of air and oxygen can be determined by the applied Coriolis mass flow meters mentioned above.

The injection time of \( \Delta t_{\text{inj}} = 0.5 \text{ s} \) leads to an overfilled detonation tube with a homogeneous distributed mixture. Depending on the applied mass flow rates, the PDC is filled within 30 to 120 ms. Hence, the influence of the transient behavior of the fuel valves during opening, which has been reported by Brophy and Hanson, can be neglected. In order to minimize the stress on the injection tubes and the mixing geometry, the fuel valves are closed 3 to 5 ms before the spark discharge. This time delay is adjusted depending on the mass flow rates to ensure a homogeneous mixture inside the PDC while minimizing the amount of fuel left inside the injection tubes.

Five piezoelectric pressure sensors \( P1-P5 \) (PCB 112A05) record the dynamic pressure at the wall of the detonation tube with a sampling rate of 1 MHz. All other sensors as well as the ignition trigger signal are recorded simultaneously which allows the recorded data to be synchronized with the measurement procedure.

### 2.2 Configurations and settings

All measurements have been performed with an injection time of \( \Delta t_{\text{inj}} = 0.5 \text{ s} \) and at an operating frequency of 0.5 Hz. The equivalence ratio was set to \( \varphi = 1 \).

Three parameters are varied for the measurements in this work: (1) the mass flow rate, (2) the concentration of oxygen in the oxidizer and (3) the blockage ratio of the orifice plate at the rear end of the PDC.

The Reynolds number of the flow can be calculated from the measured initial conditions and the mass flow rates by

\[
Re = \frac{\nu_{\text{flow}} D_{\text{tube}}}{\nu_{\text{mix}}} \tag{1}
\]

where \( D_{\text{tube}} \) is the tube diameter, \( \nu_{\text{mix}} \) is the kinematic viscosity of the reactive mixture, and \( \nu_{\text{flow}} \) is the flow...
velocity. The kinematic viscosity is calculated using a zero-dimensional Cantera reactor from the measured initial conditions and the well-known gas composition. The flow velocity can be determined by

\[ \nu_{\text{flow}} = \frac{T_0}{\rho_0 A} \sum_{\text{gas}} \dot{m}_{\text{gas}} R_{\text{gas}}, \text{gas = air, O}_2, \text{H}_2 \]  

(2)

where \( T_0 \) is the initial temperature, \( \rho_0 \) is the initial pressure, \( A \) is the cross-section area of the tube, \( R_{\text{gas}} \) is the specific gas constant and \( \dot{m}_{\text{gas}} \) is the mass flow rate of air, oxygen and hydrogen, respectively. The mass flow rate of air is varied from 27 to 78 kg/h. The oxygen mass flow rate is adjusted in a range of 9.5–28.4 kg/h in order to achieve the desired oxygen enrichment in the oxidizer of 40% vol. The fuel mass flow rate is set to 2–5.7 kg/h resulting in a constant equivalence ratio of \( \varphi = 1 \). These settings result in a Reynolds number in a range of \( 1.8 \cdot 10^4 \) to \( 5.4 \cdot 10^4 \). Four blockage ratios were applied: 0, 0.75, 0.85 and 0.90. The blockage leads to an elevated initial pressure inside the PDC, which is shown in Figure 2 as a function of the Reynolds number calculated from equation (1). Each data point represents the average of at least 50 measurements with equal settings. For a blockage ratio of 0.90 and \( \text{Re} \approx 4.7 \cdot 10^4 \), 10 measurements are examined.

The resulting initial pressure varies from atmospheric conditions to 2.6 bar. For each blockage ratio, the initial pressure increases with an increasing Reynolds number due to an increasing pressure loss at the outlet blockage.

For a slightly reduced oxygen enrichment to 35% vol. of oxygen in the oxidizer, the mass flow rate is varied for blockage ratios of 0 and 0.90. In addition, the oxygen content in the oxidizer was further reduced to 30, 25 and 21% vol. for a single constant volumetric flow rate and a blockage ratio of 0.

### 2.3 Error estimation

Repeatability was assured by measuring the initial temperature \( T_0 \) and pressure \( \rho_0 \) inside the detonation tube. Temperature measurements verified \( T_0 = 300 \text{ K} \pm 10\% \) for all experiments, which results in a relative uncertainty of 3.3% in the speed of sound. The equivalence ratio is determined to be \( 0.9 < \varphi < 1.1 \) from the mass flow rates of air, oxygen and hydrogen. The maximal relative deviation of the molar fraction of oxygen in the oxidizer is determined to be 3.5%.

### 3 Results and discussion

As explained above, the initial state and composition of the mixture can be determined from the measured static pressure, the temperature and the mass flow rates of air, oxygen and hydrogen. The pressure history inside the PDC is recorded by the sensors P1–P5. From this data, several parameters can be extracted. In all cases, the propagation speed and the amplitude of the leading shock in the pre-detonation chamber are obtained as well as the success or failure of detonation initiation. In the case of successful DDT, the velocity of both the detonation and retonation wave can be estimated and in a case of unsuccessful DDT, the velocity of the leading shock in the detonation tube can be observed.

Figure 3 shows the pressure history for sensors P1–P5 for a successful detonation initiation by shock focusing. The signals are shifted vertically by the axial position of the respective sensor so that the origin of the pressure signal matches the axial position of the sensor on the vertical axis. The scale of the pressure signal is shown in the legend and is identical for each sensor.

The leading shock can be seen as an instantaneous increase in pressure of P1 and P2. This pressure is similar to that reported by Gray et al. and Bengoechea et al. These studies focused more on the initial flame propagation and indicated speeds of around 600 m/s. These flames produce a relatively normal shock which is strong enough to generate detonation initiation in the nozzle. If the focusing of the leading shock by the converging walls of the nozzle leads to a detonation initiation, the detonation front propagates in all directions from the initiation location. Therefore, a retonation wave can be detected in the pressure data of P2 and P1. The detonation front traveling downstream exhibits characteristic detonation profiles at the sensors P3–P5. Symbols represent the detection of the three propagating pressure waves: The horizontal position
matches the time instance of detection, while the vertical position matches the axial position of the respective sensor. This allows trajectories to be drawn for the leading shock (L), the retonation wave (R) and the detonation front (D). As expected, the three trajectories have one common point that represents the detonation initiation (I) at the axial position \( x_I \). For unsuccessful detonation initiation, the three trajectories do not necessarily share one common point resulting in three different intersections \( x_{LD} \), \( x_{LR} \) and \( x_{RD} \).

Due to the pressure rise by the leading shock, the symbols representing the detection of the retonation wave for sensors P1 and P2 do not lie on the corresponding pressure signals, but rather on the respective axial positions to allow for the trajectory to be drawn. Furthermore, the detonation initiation causes structure-borne noise propagating downstream in the detonation tube at approximately 5600 m/s resulting in a ringing in the pressure signals of sensors P3–P5 before the detonation front is detected.

The mentioned features of the pressure signals are used to determine the success of detonation initiation. A successful initiation inside the shock-focusing geometry is defined by two criteria: (1) the shock velocity...
behind the nozzle (D) lies in the range of 90% to 120% of the CJ velocity (shown in Figure 4) and (2) the intersection $x_{LD}$ of the trajectories of the leading shock and the detonation wave (shown in Figure 5) is in the range from $-5$ mm to $60$ mm, i.e., close to the throat of the shock-focusing geometry. The intersection of the leading shock and the detonation has been chosen because of the small fluctuation of $x_{LD}$ for successful detonation initiation and the distinct deviation of $x_{LD}$ for unsuccessful detonation initiation. A successful detonation is only assumed if both criteria are fulfilled. It can be seen in Figures 4 and 5 that both criteria can well distinguish successful from unsuccessful DDT. This also excludes cases in which DDT occurs further downstream of the nozzle.

3.1 Detonation success rate

For gas turbine applications, the success rate of detonation initiation as a function of the operating parameters is of main interest. Therefore, the success rate of detonation initiation, defined as the number of cycles with successful detonation initiation divided by the total number of conducted cycles, is analyzed as a function of the Reynolds number $Re$, which is proportional to the mass flow rate. Figure 6 shows the success rate with respect to the Reynolds number for 40% vol. oxygen in the oxidizer and blockage ratios from 0 to 0.90. For each condition, a minimum number of 50 cycles is examined.

For $Re < 3 \cdot 10^4$, no successful detonation initiation can be observed. When further increasing the Reynolds number, the success rate increases from 0% to 100%. For $Re > 4 \cdot 10^4$, a successful detonation can be observed in almost every measurement. The blockage ratio has no visible effect on the success rate. Thus, the initial pressure has no direct influence on the success rate of the detonation initiation for 40% vol. oxygen in the oxidizer.

The success rate as a function of the Reynolds number for 35% vol oxygen in the oxidizer is shown in Figure 7. The shape of the two graphs shown is comparable to the ones for 40% vol. oxygen in the oxidizer (Figure 6). However, when decreasing the oxygen enrichment from 40% vol. to 35% vol., the critical Reynolds number increases by $7 \cdot 10^3$ for a blockage ratio of 0. For a blockage ratio of 0.90, this increase in Reynolds number is even higher. Furthermore, Figure 7 implies a visible negative influence of the blockage ratio on the success rate. The increase in blockage ratio from 0 to 0.90 leads to an increase of the critical Reynolds number.

The data of Figures 6 and 7 would seem to disagree with the assumption stated by Dorofeev et al., which suggests that the success rate can be expressed as a function of the detonation cell width. If this presumption was correct, the increase in blockage ratio in Figure 6 would lead to a decrease in cell width, and thus, successful detonation initiation would be observed at lower Reynolds numbers for higher blockage ratio. Nevertheless, it is evident that the reactivity of the mixture, which is linked closely to the detonation cell width, has an impact on the detonation initiation, since a decrease in the oxygen enrichment of the oxidizer leads to an increase in the critical Reynolds number. However, it must be noted that the transition mechanism, namely shock focusing and the Reynolds number.
number are dissimilar to those investigated by Dorofeev et al.

For an oxygen enrichment of 40% vol. and constant Reynolds number, an increase in the blockage ratio results in an elevated initial pressure due to an increased pressure drop across the outlet blockage. Assuming an ideal gas, the Reynolds number can be expressed by

\[
\text{Re} = \frac{v_{\text{flow}} D_{\text{tube}}}{\nu} = \frac{D_{\text{tube}}}{\eta R_s T} v_{\text{flow}} p_0
\]

(3)

Since the change in the dynamic viscosity \( \eta \) is negligible for all applied pressures, an increase in the static pressure \( p_0 \) leads to a decrease in the mean flow velocity for constant Re. While keeping the Reynolds number constant, the turbulence intensity \( T_u = \frac{\nu_{\text{RMS}}}{\nu} \) can also be assumed to be constant, since \( T_u = f(\text{Re}) \). This implies a decrease in the absolute velocity fluctuations. It can be stated that a decrease in \( \nu_{\text{RMS}} \) negatively affects the transition rate of detonation initiation. For an oxygen concentration of 40% vol. in the oxidizer, this effect cancels out the influence of increased pressure when increasing the blockage ratio for a constant Reynolds number. For a lower oxygen concentration in the oxidizer, the influence of increased reactivity due to an elevation in the initial pressure diminishes. This, the role of turbulence becomes more dominant. Therefore, an increase in blockage ratio, resulting in a simultaneous increase in pressure and decrease in absolute turbulent fluctuations, hinders the transition to detonation. This results in an increase in the critical Reynolds number.

In order to gain a better understanding of the underlying processes, the properties of the leading shock as a function of the initial conditions and the mixture composition are examined in the following.

### 3.2 Leading shock

Two parameters can be extracted from the pressure signals of P1 and P2 in Figure 3: (1) the time-of-flight of the leading shock \( t_{L2} - t_{L1} \) and (2) the shock amplitude \( \Delta p = p_L - p_0 \). The shock amplitude directly extracted from the pressure signal of P1 is referred to as the measured shock amplitude \( \Delta p_{\text{meas}} \) in the following. The shock velocity relative to the gas can be calculated from the time-of-flight \( \Delta t_{\text{tof}} = t_{L2} - t_{L1} \) by

\[
v_L = \frac{x_2 - x_1}{t_{L2} - t_{L1}} - v_{\text{flow}}
\]

(4)

where \( x_i \) is the axial position of the sensor \( P_i \), \( t_{L,i} \) is the time of the first pressure increase and \( v_{\text{flow}} \) is the flow velocity, which is calculated from equation (2). Since the composition and state of the gas ahead of the shock are known, the shock Mach number \( M_L \) and the post shock pressure \( p_L \) can be calculated from

\[
M_L = \frac{v_L}{a}
\]

(5)

and

\[
\frac{p_L}{p_0} = 1 + \frac{2\gamma}{(\gamma + 1)} (M_L^2 - 1)
\]

(6)

where \( \gamma = 1.4 \) is the isentropic exponent of the initial mixture. This procedure provides the calculated shock amplitude \( \Delta p_{\text{tof}} = p_L - p_0 \) from the measured time-of-flight of the leading shock.

The measured shock amplitude is found to agree well with the calculated value. The uncertainty of the calculated shock amplitude is 12% resulting from a relative uncertainty of 4% of the calculated shock Mach number. Combined with the measurement uncertainty of the measured shock amplitude of 0.5 bar, the deviation of the shock amplitudes can be well explained by measurement uncertainties.

The agreement of \( \Delta p_{\text{tof}} \) and the measured shock amplitude \( \Delta p_{\text{meas}} \) suggests the formation of a normal shock by the acceleration of the flame inside the pre-detonation chamber that propagates parallel to the tube axis. Other propagation directions would result in \( \Delta p_{\text{meas}}/\Delta p_{\text{tof}} < 1 \) since the measured velocity in the axial direction of the combustion tube would be smaller than the actual shock velocity, which would result in underestimating the calculated shock amplitude \( \Delta p_{\text{tof}} \).

Figure 8 shows the measured pressure ratio of the leading shock over the Reynolds number for 40% vol. oxygen in the oxidizer. An increase in the Reynolds number causes an almost linear increase in the pressure ratio across the leading shock for all applied blockage ratios. An increase in the Reynolds number leads to an increase in the intensity of the turbulence \( T_u = \frac{\nu_{\text{RMS}}}{\nu} \). For a constant blockage ratio, an increase in Reynolds number results in an increase in the mean flow velocity \( \bar{v} \), which implies an even stronger increase of the velocity fluctuation \( \nu_{\text{RMS}} \). The interaction of this velocity fluctuation with the flame front induces the generation of pressure waves that accumulate to form the leading shock. Hence, the amplitude of \( \nu_{\text{RMS}} \) is directly linked to the pressure ratio across the leading shock in front of the shock-focusing geometry, which explains the growth of \( p_L/p_0 \) with increasing Reynolds number.

When increasing the blockage ratio, a decrease of the shock pressure ratio is visible. Equation (3) states that an increase in the initial pressure results in a decrease in the mean flow velocity, which implies a
decrease in $v_{RMS}$ for constant Re. Thus, the pressure waves generated by the interaction of the flame and the velocity fluctuation are smaller, which results in a weaker leading shock.

As shown in Figure 2, an increase in Re leads to an elevated initial pressure. Hence, the arguments mentioned above can also be used to explain the smaller gradient of the shock pressure ratio with increasing Reynolds number for increased blockage ratios.

Figure 9 shows the pressure ratio across the leading shock for various concentrations of oxygen in the oxidizer. The blockage ratio is 0 for all data series, which implies ambient initial pressure for all measurements. A decrease in the oxygen concentration leads to a decrease in the reactivity of the mixture. Thus, the leading shock is weaker for measurements with smaller oxygen enrichment. However, the slope of the series for 40% vol. and 35% vol. oxygen in the oxidizer is similar. This is due to the fact that there is no increase in the initial pressure when lowering the oxygen enrichment.

### 3.3 Detonation initiation

The leading shock generated in the pre-detonation chamber is reflected when arriving at the converging part of the nozzle-shaped obstacle. Numerical simulations by Bengoechea et al. show that the reflection at the axially symmetric ramp of 45° leads to a circular shock structure that is focused in the center of the PDC. When the pressure and temperature in the focal point are high enough, a detonation is directly initiated. Otherwise, a deflagration is initiated that spherically propagates from the focal point. Simultaneously, further propagation of the reflected shock structure leads to two focal points traveling upstream and downstream, respectively, along the center line. When the velocities of the deflagration front and the focal point are similar, a coupling of the flame and the pressure wave is likely to occur, which represents the onset of a detonation. For this initiation mechanism, the strength of the leading shock as well as the curvature of the reflected shock structure is decisive for the success of detonation initiation.

Figure 10 shows the measured pressure ratio of the leading shock over the initial pressure for 40% vol. oxygen in the oxidizer. The data points correspond to the data evaluated in Figure 6. Here, the color...
represents the success rate from 0 (dark blue) to 1 (dark red). Two regimes are obvious: a strong shock and high initial pressure lead to successful detonation initiation by shock focusing (successful DDT), whereas a weak shock at low initial pressure ends in failed detonation initiation (No DDT). However, there is no distinct threshold between these two regimes. Rather, a third regime can be identified, where the success rate of detonation initiation lies between 0 and 1. The dotted lines represent the connection of single measurement data with the smallest pressure ratio for successful DDT and the highest observed pressure ratio that leads to unsuccessful detonation initiation, respectively.

As mentioned above, the measurement uncertainty of the pressure amplitude of the leading shock is 0.5 bar, which corresponds well with the range of the intermediate regime in Figure 10. Hence, the existence of this regime can be explained by measurement errors and this behavior is no indication for a stochastic process inside the shock-focusing geometry, but the detonation initiation rather is a deterministic process when the pressure ratio of the leading shock and the initial pressure are known accurately.

However, the increase of the success rate in Figures 6 and 7 is not due to measurement errors. This regime can be explained by the stochastic process of flame acceleration and the formation of the leading shock, since turbulence plays an essential role in this process.

### 3.4 Verification of detonation initiation by shock focusing

The pressure signals presented above suggest that the focusing of the leading shock results in detonation initiation originating from near the focal point. Numerical simulations performed by Bengoechea et al. encourage this presumption.

In order to verify this hypothesis, images were taken using a high-speed camera (Photron Fastcam SA-Z) with a frame rate of 210,000 fps for two experimental setups: (1) A transparent shock-focusing geometry made out of acrylic glass allows the axial evolution of processes inside the PDC to be observed. (2) A mirror 0.5 m downstream of the PDC outlet provides a view from the rear end of the tube. Figure 11 shows images of both configurations. Lines have been drawn onto the images in order to illustrate the inner wall of the diverging section of the nozzle. The time difference between two consecutive images is 4.762 μs. The images have been taken without an optical filter. Hence, the detected light intensity is related primarily to the emission of hot water vapor, which displays the location of combustion. The images have been inverted causing locations of high combustion rate to appear dark.

The images of the two configurations were taken during two different measurements.

The first images of both configurations show a dark spot significantly in the center of the tube at the axial position of the smallest cross-section area of the shock-focusing geometry. The brightness of the spot exceeds the brightness of all previous images and is, therefore, the

![Image](image_url)
first image shown. This spot represents the onset of the detonation subsequent to shock focusing.

In the following image, the formation of a reaction front can be observed, which propagates downstream in the subsequent images. The velocity of the reaction front in images 3 to 7 is calculated to be approximately 2500 m/s. This velocity slightly exceeds the CJ-velocity of 2250 m/s for the given conditions (atmospheric pressure, $\rho = 1$, and 40% vol. of oxygen in the oxidizer), which indicates the axial propagation of a detonation wave in these images. The front velocity between images 2 and 3 is slightly higher which can be explained by the existence of an overdriven detonation that has been observed by other groups directly after detonation initiation. This phenomenon also explains the axial position of $-5 \text{ mm} \leq x_{\text{LD}} < 60 \text{ mm}$ that has been identified as a criterion for a successful detonation initiation by shock focusing in Figure 5. For the calculation of $x_{\text{LD}}$, the detonation velocity is assumed to be constant. If the increased unsteady velocity was taken into account, the axial position of the detonation initiation would move upstream centered more closely to the throat of the nozzle. This agrees well with the high-speed images, where the detonation initiation was observed to be at the axial position of the throat of the shock-focusing geometry.

The images from the rear end of the PDC show a periodic characteristic. After the bright spot in the center in image 1, this focal point appears also in images 4 and 7, which implies a period of $t_p \approx 14\mu s$. In this time, the images visualize a structure that propagates in radial direction towards the tube wall, is reflected, and focuses again along the center line. The resulting velocity of this radial structure can be calculated from the tube diameter at the related axial position as $v_{\text{rad}} = D_{\text{tube}}/t_p \approx 1570 \text{ m/s}$. This velocity is similar to the velocity of the transverse shocks that form the cellular structure inside a propagating stable detonation. The visible structure in the high-speed images can, thus, be explained by transverse shock waves that arise from the spherical propagation of the detonation front after its initiation. In the images from the side, the only first two focal points in images 1 and 4 are visible. The last focal point in image 7 is not visible because the detonation front has already left the frame of the image.

### 4 Conclusion

A PDC test rig has been used to investigate the influence of mass flow rate and initial pressure on detonation initiation by shock focusing. Various outlet blockages have been applied in order to allow for separate examination of the influence of initial pressure and flow velocity.

Increasing the Reynolds number leads to an increase in the pressure ratio of the leading shock upstream of the shock-focusing geometry. This increase in shock strength can be explained by larger velocity fluctuations leading to the generation of stronger pressure waves at the flame front. An increase in blockage ratio results in smaller velocity fluctuations at constant Reynolds number due to a smaller mean flow velocity. A decrease in the oxygen enrichment leads to a decrease in the pressure ratio due to the lower reactivity of the mixture.

The success rate for detonation initiation inside the shock-focusing geometry is a function of the initial pressure and the pressure ratio across the leading shock. For atmospheric conditions, a critical pressure ratio of $(p_L/p_0)_{\text{crit}} = 4.3$ was found. With increasing initial pressure, the critical pressure ratio decreases.

Two processes (the generation of the leading shock and the detonation initiation by shock focusing) interact during the operation of the PDC. Two opposing effects are involved with the increase in outlet blockage for a constant Reynolds number. (1) The increase in reactivity due to a higher initial pressure supports detonation initiation, while (2) the decrease in velocity fluctuations due to smaller mean flow velocity hinders the generation of a strong leading shock, and thus, leads to a decrease in success rate of detonation initiation. For an oxygen concentration of 40% vol. in the oxidizer, these two effects cancel each other out. Hence, the success rate can be expressed as a function of the Reynolds number. However, for smaller oxygen enrichment, the second effect becomes stronger, which leads to an increase in the required Reynolds number for successful detonation initiation for increased outlet blockage.

High-speed images could be used to confirm that the shock focusing in the center of the obstacle leads to detonation initiation. Directly after the initiation, an overdriven detonation could be observed that develops to a CJ-detonation propagating downstream in the PDC. Additional structures are visible that suggest the appearance of transverse shock waves causing a periodic focusing along the center line.

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