Pressure Fluctuations in an Annular Plenum Downstream of a Multi-tube Pulse Detonation Combustor

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Abstract. The generation of large pressure fluctuations at the combustor outlet due to the periodic combustion process involving propagating detonation waves is a major drawback on the way of integrating a pulse detonation combustor (PDC) into a gas turbine. Recently, the attachment of an annular plenum downstream of a multi-tube PDC was proposed to allow for the attenuation of the pressure amplitudes. In this work, pressure data is recorded at various axial and azimuthal positions in the annular plenum allowing for a quantification of pressure fluctuations. Furthermore, a systematic study was conducted to evaluate the effect of the firing pattern and an outlet blockage on both the longitudinal change of the peak amplitudes and the pressure fluctuations throughout the entire cycle duration. The results suggest that a sequential firing pattern should be preferred over the simultaneous firing of multiple PDC tubes, as it results in the lowest pressure fluctuations at the plenum outlet.

Keywords: Pulse detonation combustor (PDC) · Annular plenum · Pressure fluctuations

1 Introduction

Pressure gain combustion has been in the scope of research in the past decades as a promising concept for increasing the thermal efficiency of gas turbines [10]. Among others, pulse detonation combustors (PDCs) revealed a promising concept to realize pressure gain combustion. The tubular combustor is periodically filled with a fuel–oxidizer mixture, which is ignited close to the combustor

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head. Commonly, the integration of geometric obstacles is used to promote the deflagration-to-detonation transition (DDT). The initiated detonation wave then combusts the remaining mixture nearly instantaneously, resulting in a considerable rise in pressure. By conducting numerical simulations, Xisto et al. [11] demonstrated that the periodically fluctuating flow conditions downstream of a PDC induce significant variations in the incidence angle of the rotor blades, which results in a reduced turbine efficiency. Fernelius and Gorrell [1] found that the decrease in turbine efficiency mainly depends on the amplitude of pressure fluctuations, while the pulsing frequency only plays a secondary role. Therefore, several investigations were conducted in the past aiming for a reduction of these pressure oscillations. Schauer et al. [9] experimentally studied the interaction of a PDC with a centrifugal turbine. They stated high losses through the turbine stage expansion. Measurements by Rouser et al. [8] revealed highly unsteady flow conditions downstream of a multi-tube PDC, which led to a decrease in the cycle-averaged efficiency of an attached turbine. Moreover, they observed a decrease in the pressure amplitude for an increasing firing frequency of the PDC, which was found to be beneficial for the turbine operation. In addition to the operation frequency of a PDC, adjusting the firing pattern has been under investigation by Rasheed et al. [5]. They found that the choice of the firing pattern affected the pressure amplitudes at the turbine inlet. Specifically, a sequential firing was observed to result in reduced fluctuations compared with a simultaneous operation of the tubes. In consistence with this, asynchronous firing of a double-tube PDC was found to be beneficial in terms of turbine efficiency by Qui et al. [4]. Rezay Haghdoost et al. [7] proposed the integration of an annular plenum as an alternative concept to achieve reduced pressure amplitudes at the turbine inlet plane downstream of a PDC. They demonstrated a reduction by nearly 70% along the plenum axis as the shock waves exiting the combustion tubes diffracted in azimuthal direction.

In this work, pressure fluctuations in an annular plenum downstream of a multi-tube PDC are examined experimentally, which allows for identifying favorable operating conditions to reduce pressure fluctuations at the plenum outlet. In particular, the propagation and interaction of shock waves inside the annular plenum are analyzed and the longitudinal change of the maximum pressure amplitude along the plenum axis is quantified for various firing patternsand operation frequencies. Furthermore, the effect of an outlet blockage on the pressure evolution and the longitudinal change of pressure amplitudes is evaluated.

2 Experimental Setup and Measurement Procedure

The experiments presented in this work, were conducted on a multi-tube PDC test rig, which is sketched in Fig. 1. The test facility consists of six PDC tubes and a plenum, arranged in can–annular configuration. Each PDC tube is composed of an injection section, a DDT section, and a detonation section. In the injection section, the fuel is added to a continuous air flow through three parallel arranged solenoid valves (Bosch 0280158827) in a jet in cross flow configuration. The

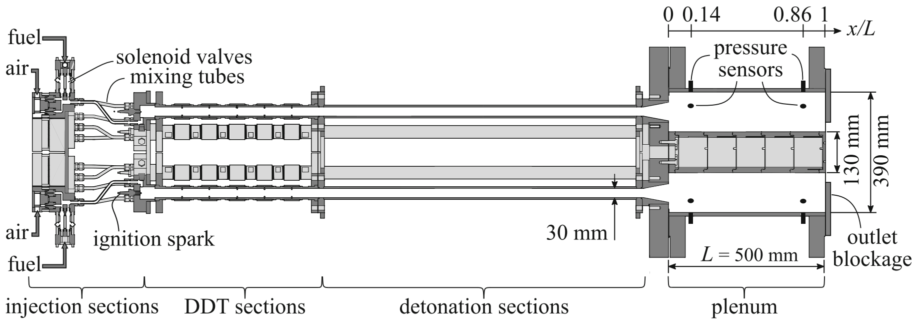

Fig. 1. Cross section of the multi-tube PDC consisting of six circumferentially arranged tubes

mixture is subsequently guided through three mixing tubes before it is radially injected into the combustion tube through three circumferentially distributed ports. A spark plug at the center of the flat combustor head allows for the controlled ignition of the injected fuel–air mixture. A time delay of 4 ms between the closing of the fuel valves and the spark discharge is applied to create an air buffer in the mixing tubes before ignition. By this, the mechanical and thermal stress on the injection section is minimized. Each DDT section is equipped with a series of orifice plates with a blockage ratio of 0.43 equally spaced at 85 mm to ensure reliable detonation initiation. Downstream of the DDT section, a straight tube with an inner diameter of 30 mm and a length of 0.8 m is attached to allow for the combustion of the injected fuel–air mixture by means of a propagating detonation wave. The transition from the PDC outlet to the annular plenum is realized by diverging nozzles increasing the cross section area of each combustion tube by a factor of 2.25. All six combustion tubes are arranged on a pitch-circle diameter of 260 mm, as sketched in Fig. 2a that visualizes a rear view of the test rig. The radial height of the annular channel is sized to match the distance of two neighboring tubes of 130 mm, while the tube outlets are located at half the channel height. Thus, the outer wall of the plenum has a diameter of 390 mm and the center body has a diameter of 130 mm. The axial length of the plenum is set to $L = 500$ mm. This length was chosen to investigate the propagation of the pressure waves emitted from the PDC tubs and to assess the attenuation of pressure amplitudes along the plenum axis, which can then be used to design an improved plenum geometry with a reduced axial length. In order to examine the effect of an outlet blockage on the longitudinal change of pressure amplitudes in the annular plenum, an orifice plate is installed at the plenum outlet. Three different orifice plates are used to achieve blockage ratios of $\beta \in [0.5, 0.7, 0.9]$, as shown in Fig. 2b. The applied blockage plates were designed to emulate the effect of a reduction of the annular cross section area, which would be required when attaching a suitable turbine with respect to the applied mass flux. Measuring the static pressure throughout the entire operation period revealed no increase in static pressure for any applied blockage. The flow through

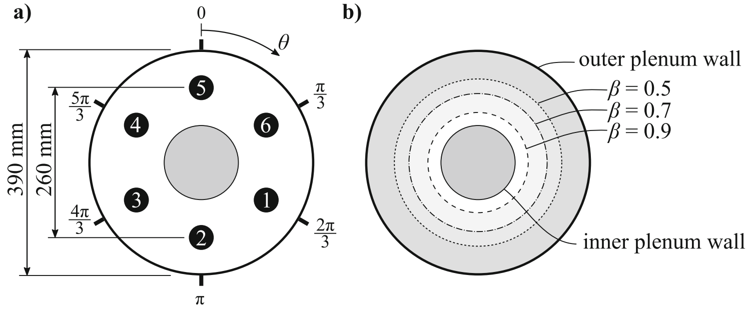

Fig. 2. Rear view of the annular plenum

the plenum exit is therefore assumed not to be choked at any time, which ensures comparable flow conditions for all conducted measurements. Two piezoresistive pressure transducers (Kulite DTL) were flush-mounted into the outer plenum wall at $x/L = 0.14$ and $x/L = 0.86$ downstream of PDC tube 5 ($\theta = 0$). An additional piezoresistive sensor was installed close to the plenum outlet on the opposite side of the plenum ($\theta = \pi$, $x/L = 0.86$). In combination with nine piezoelectric pressure transducers (PCB 112A05), this resulted in two arrays of six sensors, evenly distributed in circumferential direction, at $x/L = 0.14$ and $x/L = 0.86$ (see Fig. 1). As observed in previous experiments [7], all applied pressure transducers implied a measurement uncertainty of less than 2%. All pressure values, which are included in the following are to be considered as absolute pressure.

A continuous air flow rate of $\dot{m}_{\mathrm{air}} = 900\,\mathrm{kg/h}$ is provided for all measurements, equally distributed among six PDC tubes using a manifold. A constant mass flow rate with a maximum deviation of 0.7 % is assured by applying a closed-loop control, including the evaluation of the actual mass flow rate measured by a Coriolis mass flow meter (Endress+Hauser Promass 80A) and the adjustment of the position of an electric proportional valve (Bürkert 2712). The fuel mass flow rate during the injection period is controlled by setting the supply pressure by means of a dome-loaded pressure regulator (Swagelok RD8) to 5 bar. In previous investigations [2,3], this methodology was proven to allow for the injection of a stoichiometric hydrogen–air mixture with a nearly constant equivalence ratio along the combustor. An injection duration of 21 ms was applied, which results in the combustion tubes being entirely filled with reactive mixture. For each measurement, the PDC tubes are operated for ten consecutive cycles, with a firing frequency of 16.7 Hz ($t_{\mathrm{cycle}} = 60\,\mathrm{ms}$). Although this resulted in an operation duration of only 0.6 s, no systematic change in the recorded pressure signals over the conducted combustion cycles was observed. Thus, the recorded pressure signals and the following examination are expected to be representative for an arbitrary operation time.

Six different firing patterns, as illustrated in Fig. 3, are applied. The naming convention of the firing patterns is based on the number of simultaneously

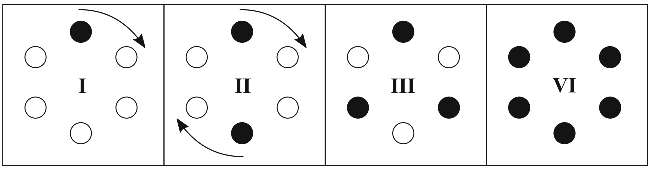

Fig. 3. Firing patterns

operated tubes. Firing pattern **I** implies sequential firing of all six tubes with a delay of 10 ms between two consecutive ignitions. Simultaneous ignition of two opposite tubes is obtained from applying firing pattern **II**. Here, the delay between two subsequent ignitions is increased to 20 ms. Alternating ignition of a set of three tubes is realized by pattern **III**. Firing pattern **VI** results in the simultaneous operation of all six PDC tubes. As the firing frequency of a single PDC tube remains constant for all patterns, the overall thermal power of the multi-tube PDC is independent of the applied firing pattern. By the variation of the number of simultaneously operated tubes n, the frequency at which shocks enter the plenum varies. This parameter is called the effective firing frequency f_{eff} and is calculated from

$$f_{\mathrm{eff}} = \frac{N}{n} f_{\mathrm{tube}}, \qquad (1)$$

where $N = 6$ represents the total number of PDC tubes.

3 Results and Discussion

In this section the evolution of the pressure waves exiting the PDC tubes and subsequently entering the annular plenum is analyzed for different firing patterns and plenum outlet blockage ratios. For this, pressure signals measured at different azimuthal and axial positions at the outer plenum wall are evaluated in the following.

3.1 Examination of Pressure Signals

In this section, the main features of the shock wave propagation inside the plenum are examined by means of pressure signals at the outer plenum wall. In addition, the impact of the firing pattern is analyzed. Once a detonation wave reaches the mixture–air intersection at the PDC outlet, it can not sustain due to the absence of reactive mixture, and thus, transitions into a propagating shock wave. Subsequently the shock wave diffracts in the divergent nozzle due to the increase in the cross section area from the PDC tube to the annular plenum. The recorded pressure amplitude p at six azimuthal and two axial positions for the operation with firing pattern **I** are shown in Fig. 4 for an example cycle. As the examination of all available data (not shown for brevity) revealed very

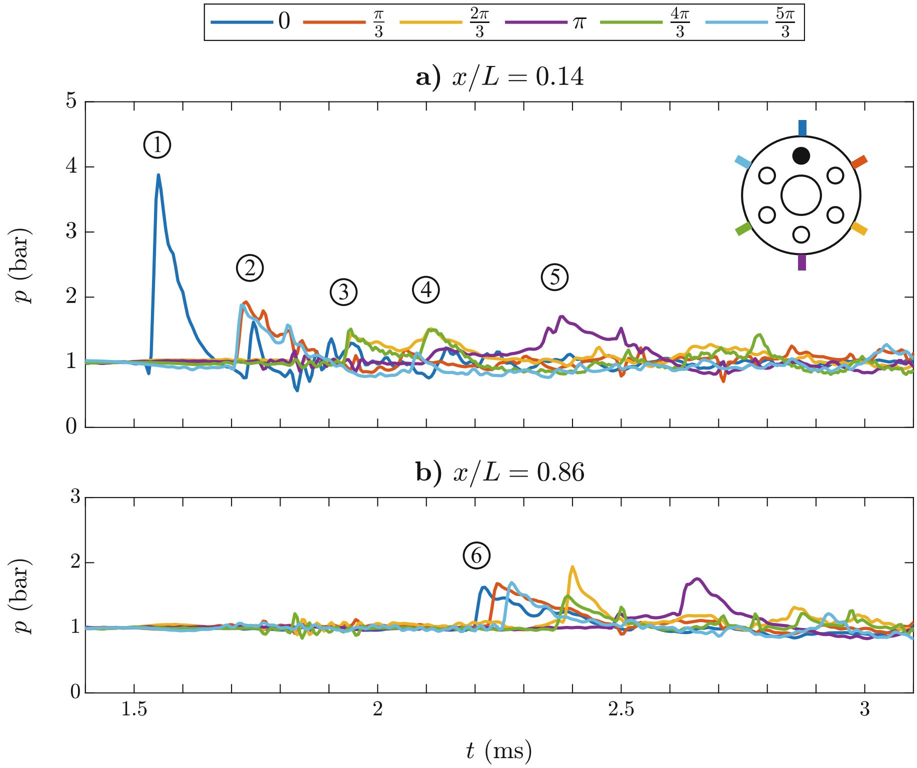

Fig. 4. Pressure histories subsequent to the firing of PDC tube 5 at two different axial positions. The PDC was operated with firing pattern **I** and $\beta = 0$.

similar pressure signals, the given example is considered to be representative. The time is given with respect to the spark discharge in the firing PDC tube.

At $t \approx 1.5$ ms, a sharp increase in pressure is detected at $\theta = 0$ and $x/L = 0.14$ ①. The maximum measured amplitude of $p_{\mathrm{max}} \approx 4$ bar is significantly smaller than the CJ pressure of $p_{\mathrm{CJ}} \approx 15$ bar, which denotes the pressure behind the detonation wave propagating through the stoichiometric hydrogen–air mixture at atmospheric conditions in the combustion tube. This decay in the pressure amplitude is attributed to two effects: i) the transition from a detonation front into a shock wave and ii) the increase in the cross section area from the PDC tube to the annular plenum. A second pressure peak is observed at this sensor position $t \approx 1.75$ ms ②, which can be explained by a pressure wave reflected at the center body [6]. Within the same period, the shock wave exiting the PDC tube propagates in azimuthal direction and evokes a sudden increase in static pressure at both $\theta = \frac{\pi}{3}$ and $\frac{5\pi}{3}$. As the pressure wave propagates further, it arrives at the azimuthal positions $\frac{2\pi}{3}$ and $\frac{4\pi}{3}$, where it induces a pressure increase at $t \approx 1.95$ ms ③. A second pressure peak is visible at these two positions at $t \approx 2.1$ ms ④. Simultaneously, a first increase in the pressure at $\theta = \pi$

is observed, which is followed by a second pressure rise at $t \approx 2.35\,\text{ms}$ ⑤. Subsequently, only minor pressure fluctuations are visible at $x/L = 0.14$. Close to the plenum outlet (Fig. 4b), the pressure signal of each sensor contains one distinct maximum, respectively. As expected, the propagating pressure wave is first detected downstream of the firing PDC tube at $\theta = 0$ ⑥. Subsequently, peaks in the pressure histories are observed according to the azimuthal distance of the sensors to the firing PDC tube. Interestingly, the maximum pressure amplitudes close to the plenum outlet are not observed downstream of the firing tube, but rather on the opposite side of the annulus at $\theta = \frac{2\pi}{3}$ and $\theta = \pi$. A discussion regarding the underlying mechanism leading to the peak pressure on the opposite side of the firing tube at the plenum outlet is given in [6]. For $x/L = 0.14$, the pressure signals at $\theta = \frac{\pi}{3}$ and $\frac{5\pi}{3}$ are very similar. The same statement holds for $\theta = \frac{2\pi}{3}$ and $\frac{4\pi}{3}$ at this axial position, which indicates a mostly axisymmetric propagation of the shock wave in both azimuthal directions. Nevertheless, at $x/L = 0.86$, notable deviations are observed for opposed azimuthal sensor positions with respect to the firing PDC tube, which have already been reported in [6]. We explain this asymmetric pressure evolution by the interaction of the shock wave exiting the PDC with acoustic modes inside the annular plenum. The existence of these mode shapes were verified in [2]. In particular, a number of rotating azimuthal mode shapes were identified, when firing pattern **I** was applied. When propagating through the plenum, the main pressure wave interacts with these acoustic modes, resulting a non-symmetric pressure evolution at $x/L = 0.86$.

To evaluate the interaction of multiple shock waves simultaneously exiting the PDC tubes, the recorded pressure signals for the operation with firing pattern **II** are shown in Fig. 5. As tubes 2 and 5 fire synchronously, two distinct pressure peaks with $p_{\max} \approx 4\,\text{bar}$ are detected at $x/L = 0.14$ for $\theta = 0$ and $\theta = \pi$, respectively ①. It should be noted that the recorded pressure signals at these azimuthal positions are not expected to be congruent, as they represent the pressure evolution due to two different detonation events. Furthermore, different sensors are installed with various measurement principles (piezoresistive at $\theta = 0$ and piezoelectric at $\theta = \pi$). In particular, a non-physical decrease in the measured pressure value for the piezoelectric transducer is assumed. Nevertheless, the recorded pressure traces can be used to analyze the propagation of the pressure waves in the annular plenum. Analogous to the findings from the operation with pattern **I**, the reflection of the shock wave at the center body results in a second pressure peak at these two sensors $0.25\,\text{ms}$ after the detection of the first shock wave ②. As the two leading shock waves propagate in azimuthal direction, they cause a simultaneous increase in static pressure at all remaining sensor positions with $x/L = 0.14$. At $x/L = 0.86$, the pressure waves first arrive at $\theta = 0$ and $\theta = \pi$ ③ as they are located slightly closer to the outlets of the firing PDC tubes than the other sensors at this axial position. In contrast to the pressure signals in Fig. 4b, a second pressure peak is observed for firing pattern **II** (Fig. 5b) at each sensor position (④ and ⑤). Both peaks are associated with the propagating leading shock waves induced from the simultaneously firing of

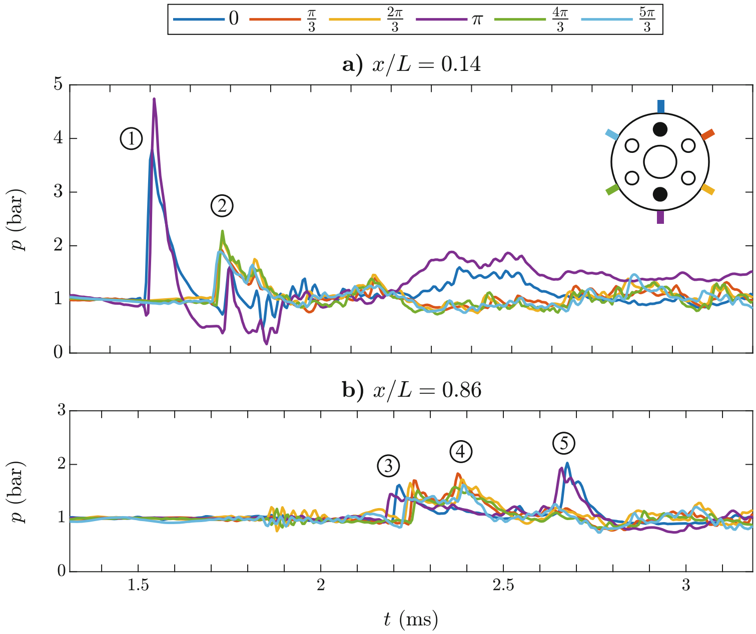

Fig. 5. Pressure histories subsequent to the firing of PDC tube 5 at two different axial positions. The PDC was operated with firing pattern **II** and $\beta = 0$.

two combustion tubes. These shock waves arrive at a given sensor position with a certain time delay due to the varying distance between the sensor position and the outlets of the two firing PDC tubes, respectively.

As discussed by Fernelius and Gorrell [1], the pressure amplitudes at the turbine inlet greatly affect the efficiency of a hybrid PDC–turbine system. However, not only the maximum peak pressure but also the distribution along the circumference is expected to impact the system performance. To allow for a quantitative examination of the azimuthal distribution of $p_{\max}$, the cycle averaged pressure amplitudes $\bar{p}_{\max}(\tilde{\theta})$ are calculated from

$$\bar{p}_{\max}(\tilde{\theta}) = \frac{1}{N_c N_t} \sum_{k=1}^{N_c} \sum_{j=1}^{N_t} p_{\max,j,k}(\theta_j + \tilde{\theta}) \tag{2}$$

with the number of combustion cycles per tube $N_c = 10$ and the number of PDC tubes $N_t = 6$. $p_{\max,j,k}$ represents the maximum pressure after firing tube j for the k-th, while θ_j denotes the azimuthal position of the firing tube. The azimuthal distribution of the cycle-averaged maximum pressure amplitude $\bar{p}_{\max}$ is visualized in Fig. 6 for all investigated firing patterns. The two lines (blue and orange) in each plot represent the values of $\bar{p}_{\max}(\tilde{\theta})$ at the two different axial positions $x/L = 0.14$ and $x/L = 0.86$, where $\tilde{\theta}$ represents the azimuthal position with respect to the firing combustion tube.

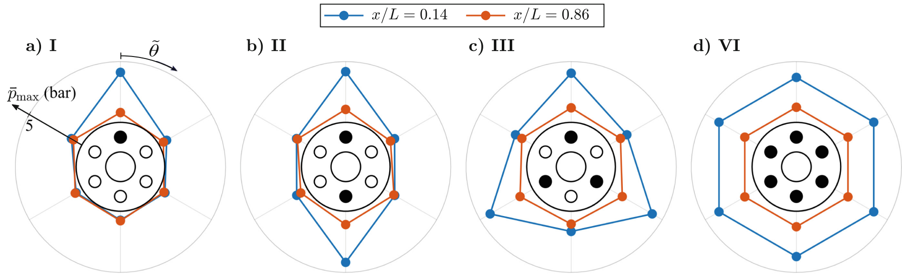

Fig. 6. Azimuthal distribution of maximum pressure amplitudes for all investigated firing patterns. The radial coordinate $\bar{p}_{\mathrm{max}}$ scale from 0 to 5 bar.

When applying firing pattern **I**, a large pressure amplitude is observed at $x/L = 0.14$ and $\theta = 0$ (Fig. 6a, blue line). This amplitude, however, is drastically attenuated along the plenum axis, resulting in a nearly homogeneous distribution of moderate pressure amplitudes close to the plenum outlet (Fig. 6a, orange line). For the simultaneous firing of two opposite tubes (pattern **II**) the amplitudes at $x/L = 0.86$ downstream of the firing tubes are increased (Fig. 6b, orange line). By further increasing the number of simultaneously firing tubes to three (pattern **III**) or even six (pattern **VI**), the pressure amplitudes at the plenum outlet increase simultaneously (Fig. 6c and d). This trend can be explained by the restricted expansion of the leading shock waves in azimuthal direction due to the coexistence of multiple shock waves, exiting the PDC from a number of simultaneously operated tubes.

3.2 Longitudinal Change of Pressure Amplitudes

The attenuation of pressure amplitudes along the plenum axis is the main purpose of integrating an annular plenum downstream of the PDC. In this work, the longitudinal change of pressure amplitudes is quantified by the pressure ratio Π, which is determined from the maximum pressure amplitudes at a given azimuthal position according to

$$\Pi = \frac{\bar{p}_{\mathrm{max}}(x/L = 0.86)}{\bar{p}_{\mathrm{max}}(x/L = 0.14)}. \qquad (3)$$

Values of $\Pi > 1$ indicate a larger maximum pressure amplitude near the plenum outlet ($x/L = 0.86$) than recorded close to the plenum inlet ($x/L = 0.14$). In contrast to this, $\Pi < 1$ indicate a longitudinal attenuation in $\bar{p}_{\mathrm{max}}$. The resulting azimuthal distributions are visualized in Fig. 7 for all investigated firing patterns and two blockage ratios of the plenum outlet, $\beta = 0$ and 0.9, respectively.

Regardless of the blockage ratio and the firing pattern, the largest longitudinal attenuation in the pressure amplitude is observed at the azimuthal positions of the firing PDC tube(s), resulting in the smallest values of Π for the respective position(s). In addition, the plenum blockage ratio β was found to have no significant impact on Π at these positions. For sequential firing (pattern **I**),

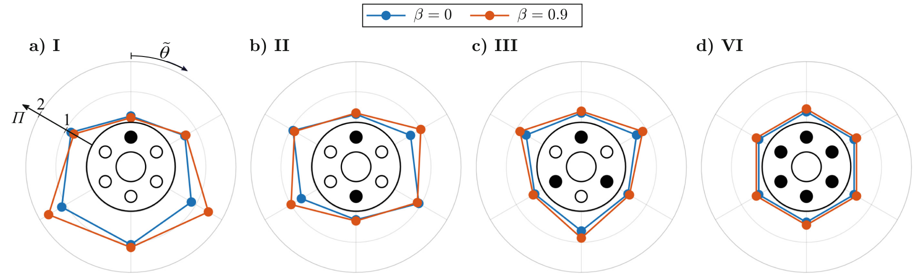

Fig. 7. Azimuthal distribution of Π for all investigated firing patterns and two blockage ratios. The radial coordinate scales from 0 to 2.

$\Pi > 1$ is observed at multiple azimuthal positions. This indicates larger pressure amplitudes at the plenum outlet compared with the plenum inlet at $\theta = \frac{2\pi}{3}$, π, and $\frac{4\pi}{3}$ in case the tube at $\theta = 0$ fires. As discussed in [7], the reflection of the leading shock at the plenum outer wall results in the formation of a Mach stem at $\theta \approx \pi$. When a plenum outlet blockage of $\beta = 0.9$ is introduced this pressure wave is reflected at the plenum outlet, resulting in a further increased pressure amplitude at $x/L = 0.86$. The azimuthal distribution of Π for firing pattern **II** visualizes a decrease in the pressure amplitude from the inlet to the outlet of the plenum for all considered azimuthal positions when firing two opposite PDC tubes simultaneously. The same findings can be deduced from the results for the operation with patterns **III** and **VI**. When comparing the azimuthal distributions of Π for the different patterns, the minimum value of Π in azimuthal direction is steadily observed downstream of the firing PDC tube(s): $\theta = 0$ for firing pattern **I**, $\theta = 0$ and $\theta = \pi$ for firing pattern **II**, and $\theta \in [0, \frac{2\pi}{3}, \frac{4\pi}{3}]$ for firing pattern **III**. For firing pattern **VI**, a homogeneous distribution of Π is obtained. When increasing the number of simultaneously operated tubes, this minimum value of Π increases gradually, which indicates a decreasing longitudinal attenuation of the maximum pressure amplitude along the plenum axis. In addition, the application of an outlet blockage results in a smaller reduction of pressure amplitudes at some distinct azimuthal positions.

In order to quantitatively compare the obtained pressure amplitudes close to the plenum outlet for all investigated firing patterns and blockage ratios, $P_{\max}$ is calculated as the average value of the maximum pressure amplitude $\bar{p}_{\max}(\tilde{\theta})$ in azimuthal direction for $x/L = 0.86$ according to

$$P_{\max} = \frac{1}{N_\theta} \sum_{i=0}^{N_\theta - 1} \bar{p}_{\max}(\theta_i), \tag{4}$$

with $\theta_i = \frac{2\pi i}{N_\theta}$. In this work, $N_\theta = 6$, as sensors were installed at six equidistant azimuthal positions. The obtained values are plotted in Fig. 8a for all applied firing patterns with respect to the blockage ratio of the plenum outlet. In addition, the circumferential average of the root–mean–square (RMS) value during the entire operation duration is determined as

$$P_{\text{RMS}} = \frac{1}{N_\theta} \sum_{i=0}^{N_\theta - 1} p_{\text{RMS}}(\theta_i). \tag{5}$$

The results are plotted in Fig. 8b.

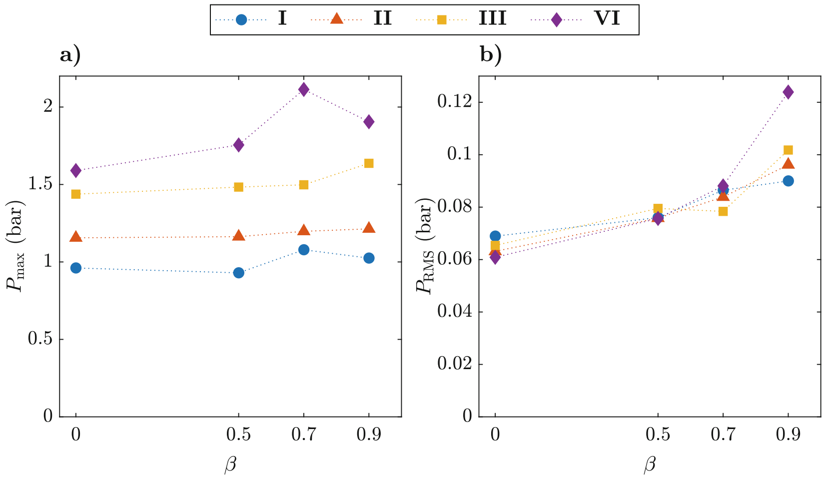

Fig. 8. (a) Cycle-averaged maximum pressure amplitude in azimuthal direction and (b) p_{RMS} at $x/L = 0.86$.

It can well be seen in Fig. 8a that an increasing number of simultaneously firing tubes significantly increases the maximum pressure amplitude along the circumference for all applied blockage ratios. When no constriction is applied to the plenum outlet ($\beta = 0$), a small reduction in the RMS value of pressure fluctuations is observed when increasing the number of simultaneously firing tubes (Fig. 8b). This trend, however, is reversed when the maximum blockage ratio of $\beta = 0.9$ is applied. In conclusion, the presented results suggest that sequential firing is favorable not only because it results in the largest longitudinal attenuation of peak amplitudes of the shock waves exiting the PDC, but also because of the smallest RMS value of pressure fluctuations, which is expected to be beneficial for the operation of an attached turbine.

4 Conclusion

Pressure fluctuations in an annular plenum downstream of a multi-tube pulse detonation combustor (PDC) were investigated experimentally. Each combustion tube was operated at a constant firing frequency of 16.7 Hz, while four different firing patterns were applied, defining the succession of firing tubes. In addition to measurements with an open plenum outlet, three different blockage plates were installed, resulting in blockage ratios of 0.5, 0.7 and 0.9 at the plenum outlet. The recorded pressure signals subsequent to a detonation event were evaluated for two arrays of six circumferentially distributed pressure sensors at different axial positions at the plenum outer wall. The observed pressure histories could well be explained by the propagation of pressure waves that originated from the propagating detonation front in the combustion tubes entering the plenum. However, the installation of additional pressure sensors or the application of planar measurement methods, e.g. particle image velocimetry, is suggested to gain more profound understanding of the propagation and the interaction of pressure waves in the annular plenum. The examination of the azimuthal distributions of the pressure amplitude confirmed, that the maximum peaks were consistently detected directly downstream of the firing PDC tubes. This amplitude was drastically attenuated along the plenum axis, which was attributed to the diffraction of the pressure wave in azimuthal direction. For a sequential firing pattern, a growth in pressure amplitudes was observed from the inlet to the outlet of the plenum on the opposite side of the firing tube. This effect was even more pronounced, when an outlet blockage was applied. When increasing the number of simultaneously firing tubes, the longitudinal attenuation of the maximum pressure amplitude was reduced, which resulted in larger peak pressure values at the plenum outlet for these firing patterns. The application of an increasing blockage ratio at the plenum outlet enhanced this deviation between the investigated firing patterns. The evaluation of the root–mean–square value of pressure fluctuations throughout the entire operation duration at the plenum outlet revealed a considerable increase in pressure fluctuations for an increasing number of simultaneously firing tubes when a blockage ratio of 0.9 was applied. In contrast to the results from the operation with an open plenum outlet, the findings from the examination with the largest applied blockage ratio revealed that the sequential firing of the PDC tubes is favorable to reduce pressure fluctuations at the inlet of a potentially attached turbine.

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