# Part Load Control for a Shockless Explosion Combustion Cycle

**Florian Arnold, Giordana Tornow and Rudibert King**

**Abstract** Since a significant increase in the efficiency of conventional gas turbines is unlikely due to various reasons, new concepts are needed. One option is to redesign the thermodynamic process itself. Replacing the constant pressure combustion with constant volume combustion (CVC) offers such an increase in efficiency. A promising new process that approximates constant volume combustion is the so-called shockless explosion combustion (SEC). SEC utilizes a homogeneous auto-ignition inside a combustion tube to avoid gas expansion during combustion. An acoustic interaction within the tube is exploited to ensure a self-sustained cyclic operation. For this, chemical and acoustic time-scales have to match. As this is impossible under ambient pressure conditions, for which SEC has been tested experimentally, this study focuses on simulations that mimic the situation of elevated pressure to design a controller. Herein, a control system is introduced within the numerical simulation of SEC that is capable of driving the process to different operating points. It expands on an iterative learning control from recent publications, which adjusts ignition time over the length of the tube. The control system proposed here can be used to realize a part load operation within the observed simulation.

**Keywords** Iterative learning control · Part load · Shockless explosion combustion

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## Nomenclature

| | |
|---|---|
| SEC | Shockless explosion combustion |
| ILC | Iterative learning control |
| $\Psi$ | Hammerstein compensator |
| $\tau$ | Ignition delay time |
| $\underline{b}$ | Model offset |
| $E_k$, $E_{max}$ | Energy |
| $\underline{e}$ | Control error |
| $e_P$ | Position control error |
| $e_{T_F}$ | Fuel injection error |
| $\underline{f}_k$ | Fuel injection curve |
| $\mathbf{G}$ | Model matrix |
| $\mathbf{I}$ | Identity matrix |
| $J$ | Cost function |
| $k$ | Cycle index |
| $\mathbf{L}$ | Learning matrix |
| $m$ | Number of ignition sensors |
| $n$ | Size of the control trajectory |
| $\underline{r}$ | Ignition time reference |
| $r_P$ | Reference position |
| $t_{ign,x}$ | Ignition time at position $x$ with respect to the beginning of the injection |
| $\underline{u}_k$ | Control trajectory (ignition delay time) |
| $\underline{\tilde{u}}_k$ | Injection trajectory (ignition delay time) |
| $\Delta\underline{u}$ | Change of the control trajectory |
| $\mathbf{W}_e$, $\mathbf{W}_{\Delta u}$, $\mathbf{W}_r$, $\mathbf{W}_V$ | Weighting matrices |
| $w_u$, $w_r$, $w_V$ | Weighting parameters |
| $\underline{y}_k$ | Control variable (ignition time) |

## 1 Introduction

Gas turbines provide safe and reliable energy conversion to produce electric energy or thrust in aircrafts. The efficiency of gas turbines has been improved substantially over recent decades, but currently approaches a plateau. A further increase would require a higher turbine-input temperature, which state-of-the-art turbines cannot handle. For a significant improvement in efficiency, an optimization of the combustion cycle itself offers high potential. Conventional gas turbines rely on the Joule cycle, which assumes combustion with constant pressure. By replacing the combustion with constant volume combustion (CVC), efficiency can be increased. The resulting Humphrey cycle provides a higher amount of usable work for the same initial conditions. An innovative process that approximates a constant volume combustion is the so-called shockless explosion combustion (SEC), which was first introduced by Bobusch et al. [1].

The SEC process consists of several phases that run in a sequence before starting over again. A single cycle with all phases is shown in Fig. 1. At the beginning of a cycle, the combustion tube is filled with a combustible mixture of fuel, an air buffer, and the remaining exhaust gas of the previous combustion. The fuel-air mixture, and by this the ignition delay time, is stratified during the fuel injection process in order to compensate for variations in the residence time of individual fuel particles and finally achieve a homogeneous auto-ignition. Since the ignitable mixture is sensitive to high temperatures, it is separated from the hot exhaust gas by an air buffer. That way, premature ignition is avoided (see phase I in Fig. 1). After the homogeneous auto-ignition of the fuel-air mixture takes place, the pressure and the temperature rise within the related part of the tube. A pressure wave propagates downstream to the outlet on the right (phase II) and is reflected as a suction wave (phase III). When the suction wave reaches the closed inlet on the left side, the pressure drops below the input pressure (phase IV). This allows a refilling of the tube with a fresh air buffer followed by the fuel-air mixture (phase V). Berndt [2] assumes, as an order of magnitude estimate, that 40% of the tube has to be filled with the fuel-air mixture for a full load SEC operation. In this contribution, we will study the effect of lower fillings to realize a part load operation. For a detailed introduction to SEC, see Bobusch et al. [1].

This work assumes that SEC replaces the conventional combustion in a gas turbine. One of the main advantages of gas turbines is their ability to quickly change between different operating points. For most gas turbines, this is done by lowering the fuel effort, which implies a lower heat addition within the combustion cycle. It is thus necessary that a process like SEC be able to be adjusted easily to react to different demands. However, due to the intricate relation between chemical and acoustic timescales, as proposed in the original idea of SEC [1], it is not obvious how this could be achieved. Moreover, the controller that has been proposed so far [3] has resulted in a homogeneous auto-ignition within a combustion region that did not start at the inlet of the tube. The scope of this work therefore will be the introduction of a control system that provides the capability of driving the SEC process to requested part load points of operation, i.e., set-points holding these states, and achieving ignition from the start of the tube.

Recent investigations [4] have shown that resonant operation of SEC is not possible with affordable equipment under the ambient conditions that have been studied

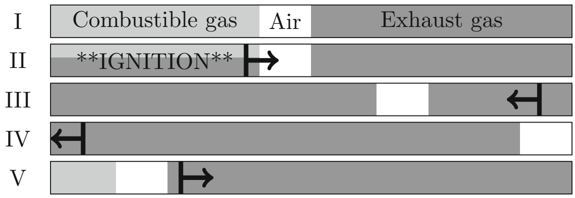

**Fig. 1** SEC cycle

experimentally so far. Since the development of a part load control system requires a stable resonant operation, the approaches in this work are implemented within a numerical simulation of SEC with an elevated pressure. The used 1-D Euler simulator built by Berndt [2].

The remainder of this contribution is organized as follows: Sect. 2 presents a short overview over the numerical SEC simulation followed by a definition of the term part load for the SEC process in Sect. 3. Based on this, a control system is introduced in Sect. 4 that is capable of driving and holding the process from full load to part load and back. At the end, in Sect. 5, representative results are shown to illustrate how the system handles different requirements, before conclusions are drawn in Sect. 6.

## 2 Simulation of the Shockless Explosion Combustion

The numerical simulator of the SEC process used here was developed by Berndt [2] and has since been maintained by Tornow in Klein's group at FU Berlin. The simulation is restricted to a 1-D regime and is based on the Euler equations extended by chemical kinetics. The fuel used within the simulation is hydrogen. This choice is motivated by similar CVC studies, although hydrogen necessitates unrealistically long combustion tubes. That is a result of the inert ignition behavior of hydrogen. The combustion behavior is approximated by the detailed $H_2/O_2$ kinetic model introduced by Burke et al. [5]. The reaction mechanism includes 11 substances and more than 20 reaction paths.

Since it is planned that the SEC process works within a gas turbine, it is essential to define appropriate, realistic boundary conditions. To model the inlet of the tube, a pressure-related boundary condition has been implemented. A constant pressure and temperature generated by a compressor is assumed in front of the tube. If the pressure inside the tube is higher than the pressure provided by the compressor, the boundary is considered to be closed. The solid wall is implemented by using ghost cells that reflect the state of the first cell after the inlet. In contrast, if the pressure inside the tube drops below the compressor output pressure, the boundary condition models an isentropic inflow into the tube. The ghost cell before the inlet is then set according to the state reached by adiabatic expansion from the compressor output state.

For simplicity, neglecting a plenum behind the tube and neglecting a detailed turbine model, the open end of the tube at the outlet is modeled by an isentropic expansion to the pressure level of a hypothetical plenum, which is assumed to have the same pressure as the compressor outlet. This is followed by a very simple turbine model with an ideal isentropic expansion to atmospheric conditions.

Since the described simulation setup is mainly used for theoretical investigations, the dynamic behavior of sensors and actuators is not considered within the calculations. For the application at a physical test rig, these additional aspects have to be taken into account.

## 3 Part Load of SEC

This work proposes a part load control for the SEC process in the context of a gas turbine. It is thus necessary to take a look at the term *part load* operation and clarify it for SEC. The part load operation of the SEC is defined by the amount of energy output $E_k$ within a cycle $k$. Every state with an energy output below the maximum, $E_k < E_{max}$, can be considered as a part load set-point. The highest amount of energy is available at the outlet if a homogeneous auto-ignition occurs in the largest possible region of the combustion tube. The combustible region as shown in Fig. 1 during phase I is located between the tube inlet and the air buffer. The combustion region is bounded by the size of the air buffer that is necessary to separate the combustible mixture upstream and the hot exhaust gas from the last cycle further downstream. To avoid premature ignition of the fuel-air mixture by the hot exhaust gas, the air buffer size is set to 10% of the length of the tube. This spatial separation leaves enough space between both parts, even when some gas mixes with the air buffer. It is assumed that under full load conditions, at the beginning of every cycle, the tube is filled with the gas of two cycles. The first 50% after the inlet contains the gas of the current cycle, and the other 50% consists of the gas of the previous combustion. This leaves about 40% of the length of the tube for the combustion itself. A full load operation thus requires a homogeneous auto-ignition, which implies a constant volume combustion, in the first 40% of the tube behind the inlet.

The SEC process offers two options to reduce heat release during the combustion, or the energy output of one cycle. The common way, used for conventional gas turbines, would be the adjustment of the equivalence ratio. A lower equivalence ratio would result in a lower temperature and pressure rise. Consequently, a lower energy emission at the outlet would be seen. But since a variation of the equivalence ratio has to be used in the SEC to realize fuel stratification, an additional requirement for a low-averaged equivalence ratio might increase the auto-ignition time scale relative to the shortest ignition delay and therefore disturb the resonant operation. Therefore, the size of the combustion region as a second option is used here to reduce the fuel effort and lower the energy output.

The size of the combustion region can be scaled by the size of the air buffer. A larger air buffer leads to a decreased region of combustible mixture upstream and thus also diminishes energy emission at the outlet. The adjustment of the combustion region is independent of the control for the ignition time. Therefore, the timescale of the ignition delay is not influenced during part load operation. This is an important aspect since the efficiency of the SEC process mainly depends on a reliable homogeneous auto-ignition.

## 4 Combustion Control

To change the operating point of SEC, the controller has to adjust the size of the combustion region and generate a fuel stratification that ensures homogeneous auto-ignition. As these two aspects are independent from each other, it is possible to consider both parts separately. A short summary of fuel stratification is presented first, as this task was already successfully solved for full load operation. Then, the new control of the combustion region will be included.

## 4.1 *Control of the Fuel Stratification*

To achieve homogeneous auto-ignition inside the combustion tube, it is necessary to adjust the ignition delay time as a function of the distance from the tube's inlet, i.e., as a function of the total residence time of a fuel particle before combustion. In experimental investigations, ignition is detected by several photomultipliers [4]. For the theoretical analysis considered here, the ignition time is calculated for simplicity in every grid cell of the numerical scheme. For practical use, the relevant data for ignition detection, like spatial pressure and temperature values, have to be estimated from available measurements. Such a state estimation approach for SEC has been already introduced by Schäpel et al. [6] and will be part of future work concerning part load operation. The ignition delay time depends on the equivalence ratio, the temperature, and the pressure of the fuel-air mixture. Since the last two parameters cannot be adjusted easily, fuel stratification is the only option to command the ignition delay time.

Regarding the cyclic characteristic of SEC, it seems reasonable to use an iterative learning controller (ILC), which improves fuel stratification from cycle to cycle. Such an ILC setup for SEC simulation has been introduced in a former study of full load operation [3]. As the scope of this work is focused on control of the length of the combustion region, the ILC system and the applied model will only be summarized shortly in the next two sections, giving further details not presented previously [3].

### 4.1.1 Model

ILC relies on a linear model that describes the impact of the control trajectory $\underline{u}_k \in \mathbb{R}^n$ on the control variable $\underline{y}_k \in \mathbb{R}^m$, where $\underline{u}_k$ and $\underline{y}_k$ contain the sampled values of one cycle $k$. Due to real-time requirements and technical restrictions, the numbers $n$ and $m$ of input and output variables, respectively, had to be limited in the experimental investigation of SEC [4]. This makes sense in the simulation study as well, as tests have shown. However, for the numerical simulation, a finer discretization of the input with a time increment $\Delta t$ has to be chosen. As will be seen below, the control input to be calculated by the controller will be chosen, rather unconventionally, as commanded ignition delay times $\tau$. To that end, a linear interpolation is applied to obtain $\underline{\tilde{u}}_k = [\tau_1, \tau_2, \dots, \tau_q]^T$ for $t_j = j\,\Delta t < t_{0,k} + T_{F,k}$ and $j = \{1, 2, \dots, q\}$ from the actual control trajectory $\underline{u}_k = [\tau_1, \tau_2, \dots, \tau_n]^T$ The time $t_{0,k}$ specifies the beginning of the injection for cycle $k$ and $T_{F,k}$ is the fuel injection duration. The trajectory $\underline{\tilde{u}}_k$ with an ignition delay time for every time instance of the simulation can then be used to compute the necessary equivalence ratio for this commanded

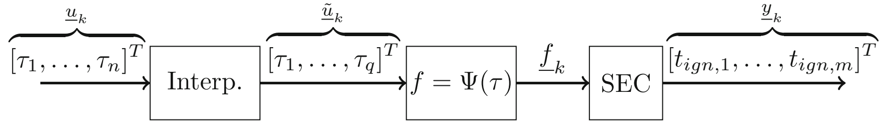

**Fig. 2** Hammerstein compensator

value by a steady non-linear map. This non-linear map $f = \Psi(\tau)$ can be interpreted as a Hammerstein compensator, Fig. 2, as an almost linear relation between the commanded ignition delay time $\tilde{\underline{u}}_k = [\tau_1, \tau_2, \ldots, \tau_q]^T$ and the actually measured ignition times $\underline{y}_k = [t_{ign,1}, t_{ign,2}, \ldots, t_{ign,m}]^T$ is obtained. The Hammerstein map is generated from a detailed zero-dimensional combustion model that assumes constant pressure and temperature.

If in cycle $k$ an ignition is detected in $m$ spatial grid cells, the ignition times $\underline{y}_k = [t_{ign,1}, t_{ign,2}, \ldots, t_{ign,m}]^T$ can be calculated with respect to the beginning of the injection in this cycle. The impact of the actual control trajectory $\underline{u}_k = [\tau_1, \tau_2, \ldots, \tau_n]^T$ represented by a number of commanded ignition delay times on the ignition time $\underline{y}_k = [t_{ign,1}, t_{ign,2}, \ldots, t_{ign,m}]^T$ for cycle $k$ can then be approximated by linear model:

$$\underline{y}_k = \mathbf{G}_k \cdot \underline{u}_k + \underline{b}_k(t_I). \tag{1}$$

The additional vector $\underline{b}_k(t_I)$ contains the offset, which results from the time a fuel particle is injected. As the combustion region might vary between different cycles of SEC, the model has to be adapted to the current combustion cycle. This may cause adaptions of the dimensions of $\mathbf{G}_k$, $\underline{b}_k$, and $\underline{y}_k$ as well. For more detailed information about the model in Eq. 1, see Rähse et al. [3].

### 4.1.2 ILC

An iterative learning control improves the injection trajectory $\underline{u}_k$ from one cycle to the next. The ILC takes the measurement $\underline{y}_k$ of one cycle and calculates an improved trajectory $\underline{u}_{k+1}$ for the next cycle. During one cycle, the controller does not adjust the control trajectory, as the already-injected fuel cannot be corrected. The improvement is based on a model like Eq. (1), which describes the relation between the control trajectory $\underline{u}_k$ and the controlled variable $\underline{y}_k$.

For cycle $k+1$, the control error $\underline{e}_{k+1} = \underline{r} - \underline{y}_{k+1}$ can be calculated from the reference $\underline{r}$ and the measurement $\underline{y}_{k+1}$ for this cycle. In case of SEC, the vector $\underline{r}$ contains identical entries specifying the time of ignition. The controller aims to find a control trajectory $\underline{u}_{k+1}$ that minimizes the control error concerning a given norm $||\underline{e}_{k+1}||_{\mathrm{W}_e}$. Using the assumed model, Eq. (1), the control error of cycle $k+1$ can be calculated as follows:

$$\underline{e}_{k+1} = \underline{r} - \underline{y}_{k+1} = \underline{r} - \underline{b} - \mathbf{G}\,\underline{u}_{k+1} \tag{2}$$

If Eq. (1) described real behavior perfectly, it would be possible to analytically calculate the necessary control trajectory $\underline{u}_{k+1}$ that would minimize the following cost function:

$$J_{k+1} = ||\underline{e}_{k+1}||_{\mathbf{W}_e} = \underline{e}_{k+1}^T\,\mathbf{W}_e\,\underline{e}_{k+1}. \tag{3}$$

But since the model might be inaccurate, the cost function, Eq. (3), has to be expanded by an expression that penalizes the change of the control trajectory $\Delta\underline{u}_{k+1} = \underline{u}_{k+1} - \underline{u}_k$ to increase robustness:

$$J_{k+1} = \underline{e}_{k+1}^T\,\mathbf{W}_e\,\underline{e}_{k+1} + \Delta\underline{u}_{k+1}^T\,\mathbf{W}_{\Delta\underline{u}}\,\Delta\underline{u}_{k+1}. \tag{4}$$

The positive definite, symmetric matrices $\mathbf{W}_e \in \mathbb{R}^{m\times m}$ and $\mathbf{W}_{\Delta\underline{u}} \in \mathbb{R}^{n\times n}$ weight the control error and the change of the control trajectory, respectively. The cost function, Eq. (4), can be used to find the optimal control trajectory in every iteration. By choosing the optimum for every cycle, the algorithm gets closer to the minimal control error iteratively.

To find the minimum of the cost function, the derivative with respect to $\underline{u}_{k+1}$ is computed, set to zero, and solved for $\underline{u}_{k+1}$. As the reference $\underline{r}$ and the disturbances $\underline{b}$ are assumed to be invariant for all cycles, Eq. (2) is also applicable for cycle $k$:

$$\underline{r} - \underline{b} = \underline{e}_{k+1} + \mathbf{G}\,\underline{u}_{k+1} = \underline{e}_k + \mathbf{G}\,\underline{u}_k \tag{5}$$

Using this expression finally leads to the ILC law:

$$\underline{u}_{k+1} = \underline{u}_k + \mathbf{L}\,\underline{e}_k, \tag{6}$$

$$\mathbf{L} = \left(\mathbf{W}_{\Delta u} + \mathbf{G}^T\mathbf{W}_e\mathbf{G}\right)^{-1}\mathbf{G}^T\mathbf{W}_e \quad . \tag{7}$$

The adjustment of the control trajectory depends on the learning matrix $\mathbf{L}$, which contains all model information.

## *4.2 Control of the Size of the Combustion Region*

The extent of the combustion region is mainly influenced by the size of the air buffer represented by air injection time $T_{Air,k}$ and the fuel injection duration $T_{F,k}$. For part load operation of SEC, the controller mainly has to follow a required reference for the length of the combustion region. When the power requirement is reduced or increased, the air buffer size has to be adjusted accordingly. However, if the air buffer size changes, the impact of the suction wave might vary from one cycle to the next. This results in a variation of the low pressure period at the inlet necessary for sucking in fresh air, which is paraphrased here as valve opening and closing times at the inlet. If a constant fuel injection duration $T_{F,k}$ were applied, one of two different problems are likely to occur. For a valve closing before the fuel injection was completed, a part of the current control trajectory would have to be dropped. This would lead to incorrect information about the influence of the control trajectory, as described by Eq. (1), if not accounted for appropriately. Thus, the results of the other controller, the ILC for the ignition time control, might be impaired.

In contrast, a too-long phase with an open valve could evoke a second, undesired air buffer behind the fuel-air mixture, as fuel injection would end earlier. After the ignition, a second pressure wave travelling to the left would occur. This would be reflected at the closed inlet after passing through the small air buffer between the combustion region and the inlet. This unwanted pressure wave would interact in an undesired fashion with the other pressure/suction waves and might disturb the resonant operation of SEC. For this reason, two controllers are proposed here for the combustion region control. One will be responsible for the position of the air buffer, and the other for the timing between injection and the period of low pressure.

A sketch of the injection process is shown in Fig. 3 in an x/t-diagram. It shows the time from the beginning of the air injection until the ignition on the vertical axis and the axial location inside the tube on the horizontal axis. The error $e_P$ describes the difference between the last spatial element for which an ignition was detected in the last cycle and a reference position $r_P$. Accordingly, an error $e_{T_F}$ is calculated between the end of the fuel injection duration $T_F$ and the time $T_V$ the valve closes, see Fig. 3. The goal is to adjust both values, $T_{Air,k}$ and $T_{F,k}$, so that, at the moment of the first ignition, an ignitable fuel-air mixture lies exactly between the inlet and a given position of the tube. This was not possible with the previously proposed controller [3]. The desired position $r_P$ is the reference that can be changed to decrease or increase the main control variable for part load control, i.e., the length of the combustion region.

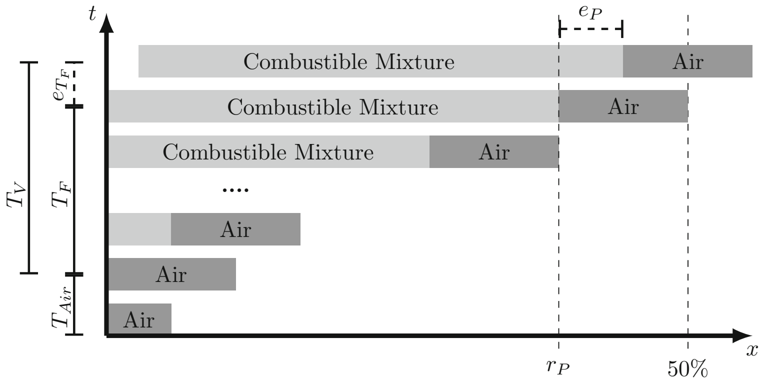

**Fig. 3** SEC injection process

The end of the combustion region can be manipulated by the air injection time $T_{Air,k}$. It is thus intuitive that a first controller commands the air buffer size based on the error $e_P$ between the desired and the detected ends of the combustion region in the last cycle. Since this is a pretty basic control task, a PI controller is applied to adjust the air buffer size. To support the controller, an additional feed-forward control $F_{T_{Air,k}}(r_P)$ is implemented to adjust the air buffer to the current set-point. The fresh air inflow duration for cycle $k$ is calculated by Eq. (8). The values for the feed-forward control for a given reference are calculated from a map that contains the steady-state solutions for the set-points. The control law, directly specifying a time, reads as follows:

$$T_{Air,k+1} = F_{T_{Air,k}}(r_P) + P_{T_{Air}} \cdot e_{P,k} + I_{T_{Air}} \sum_{i=1}^{k} e_{P,i} \ , \tag{8}$$

with proportional and integral gain $P_{T_{Air}}$ and $I_{T_{Air}}$, respectively. A second PI controller is set up to command the fuel injection duration $T_{F,k+1}$ based on the observed error $e_{T_F,k}$ between injection duration and the time during which the valve was open in the last cycle. A feed-forward control $F_{T_{F,k}}$ is implemented for the fuel injection duration as well, similar to the air buffer control. The fuel injection duration $T_{F,k+1}$ for cycle $k+1$ is calculated by Eq. (9):

$$T_{F,k} = F_{T_{F,k}} + P_{T_F} \cdot e_{T_F,k} + I_{T_F} \sum_{i=1}^{k} e_{T_F,i} \tag{9}$$

All parts of the control system interact with each other. Figure 4 shows a diagram of the whole system to illustrate the dependencies. These relations have to be considered for the controller tuning that will be described in the following section. A main aspect is the interaction between the control for the size of the combustion region to realize variable load and the ILC responsible for homogeneous auto-ignition. The time-span the control trajectory $\underline{u}_k$ of ILC considers has to be adapted according to the length of the combustion region. A close-to-constant length for the combustion region will improve the results of ILC noticeably.

## *4.3 Controller Tuning*

The complete control system handles individual aspects of the SEC process. Although all parts of the control system are set up separately, the interaction between the single controllers has to be considered. Therefore, each controller of the system has to be tuned properly to obtain a satisfying performance for the whole system. More specifically, the controllers must be designed such that they work on different time scales.

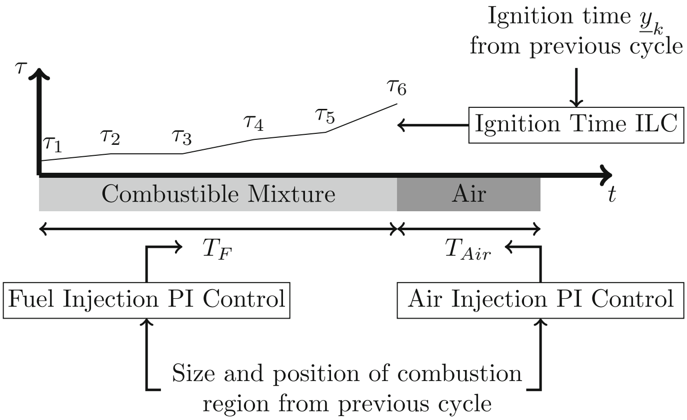

**Fig. 4** Diagram of the control system

ILC for the ignition time control is the most important aspect with respect to the SEC process. A proper SEC operation is not possible without a homogeneous auto-ignition. Thus, all parameters of the PI controllers are set with regard to the ignition time controller, which is designed first. Since previously [3] we were able to produce adequate results with an ILC system for full load operation, the same parameter settings are adopted for this work as well. This includes the weighting of the absolute control error $\mathbf{W}_r$ as well as the penalization of its variance with $\mathbf{W}_V$ within the cost function, see Eq. (4) and Rähse et al. [3] for more details:

$$\mathbf{W}_e = \mathbf{W}_r + \mathbf{W}_V \tag{10}$$

$$\mathbf{W}_r = w_r \, \mathbf{I} \tag{11}$$

$$\mathbf{W}_V = w_V \, \frac{1}{m-1} \left( \mathbf{I} - \frac{1}{m} \mathbb{1} \right) \tag{12}$$

The parameters are set to $w_r = 1$ and $w_V = 2$ so that the variance between the detected ignition times is considered more important than the absolute control error. This setting relies on the assumption that it is more important for the ignition to be as homogeneous as possible than to achieve an exact ignition time. Additionally, the change of the control trajectory is also penalized as follows:

$$\mathbf{W}_{\Delta u} = w_u \mathbf{I}. \tag{13}$$

This generates a robustification of the ILC algorithm. To avoid overshoots, the weight for the change is set to $w_u = 20$. This tuning ensures that ILC converges within the first 50 cycles.

Since ILC works best for a combustion region with a constant length, the controllers for the air buffer and the fuel injection duration have to work much faster

**Table 1** Controller settings

| Parameter | P | I | |
|---|---|---|---|
| Fuel injection time $T_F$ | 0.7 | 0.2 | |
| Air buffer size $T_{Air}$ | 0.5 | 0.2 | |
| Parameter | $w_r$ | $w_V$ | $w_u$ |
| Ignition time | 1 | 2 | 20 |

than the ignition time control. A constant size of the combustion region should be reached as soon as possible so that ILC may start improving the combustion itself. The parameters for both PI controllers are set to reach the reference within 5–10 iterations, depending on the point of operation. All parameters for the control system are shown in Table 1. To avoid interference of both PI controllers, the fuel injection PI control works slightly faster than the air buffer control. To avoid unintended behavior when switching between set-points, both PI controllers are reset. They are also turned off for 10 cycles after the set-point change while the feed-forward control drives the process toward the new set-point.

# 5 Results

The part load control was tested for hydrogen combustion and compressor pressure ratios between 24 and 50. The conditions are similar to the work of Rähse et al. [3]. However, the results shown in this section are focused on a single compressor pressure ratio, as the results for all considered values show a similar trend. The following results are calculated for a compressor pressure ratio of 34 and a temperature of around 919 K. It should be noted again that $H_2/O_2$ is a poor choice for SEC due to the immense length of the combustion tube needed [7]. At this set-point a tube length of 19.16 m would be required. Other fuels, such as dimethyl-ether, would feature significantly shorter lengths even for much smaller pressure ratios. For this study, the spatial grid resolution was set to 100 cells. The reference ignition time for the ILC is $\underline{r} = 45$ ms, since this is the minimal ignition delay time for these conditions and thus the fastest ignition that is possible.

## *5.1 Control of the Size of the Combustion Region*

A sequence of set-points was used that required the system to initially run with a combustion region of $r_P = 40\%$ of the tube's length for 50 cycles and then drive down to $r_P = 20\%$ for 100 cycles before returning to full load, $r_P = 40\%$. It has to be pointed out that all three sub-controllers were running in this simulation, the

ILC and both PI controllers. The detected end of the combustion region is shown in Fig. 5. At the beginning, the system reached the set-point after fewer than 20 cycles. This is a very satisfying result since ILC also had to change the fuel injection substantially because the optimal control trajectory $\underline{u}_k$ was unknown at the beginning. Furthermore, the choice of the initial conditions had a major influence during the first iterations. The responses following subsequent set-point changes showed that the controllers drove the process closer to the new set-points in fewer cycles. The controller for the size of the combustion region was able to adjust new set-points seamlessly and avoid large overshoots. Furthermore, the controller maintained the process at a desired operating point. The remaining variation of 1% is a result of the spatial grid resolution of the simulation.

Figure 6 shows the injection time for the air buffer on the left and for the fuel on the right. It is noticeable that the variation of the air buffer is much smaller than the modulation of the fuel injection time. This is a result of the different response times of the two PI controllers. The PI control of the fuel injection time responded slightly faster. Therefore, the fuel injection time controller already counteracted the disturbances before the air buffer PI controller started to respond.

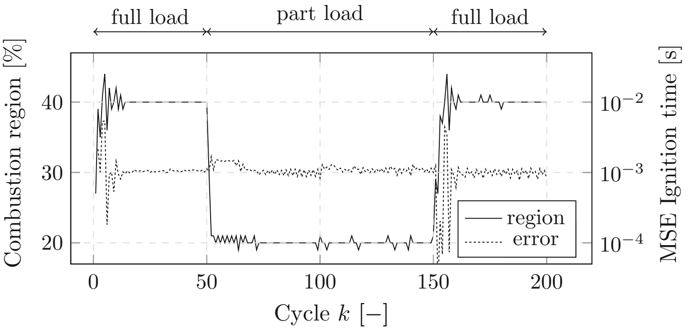

**Fig. 5** Combustion region and mean squared error (MSE) of ignition time

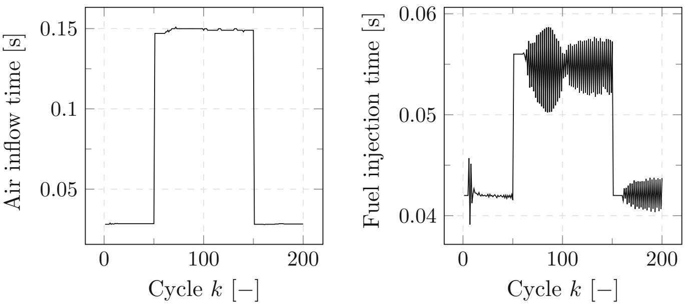

**Fig. 6** Air buffer injection duration (left) and fuel injection duration (right)

### 5.2 Ignition Time Control

When the combustion region decreases in size during a part load operation period, it is essential that ILC still guarantees the homogeneous auto-ignition necessary to approximate a constant volume combustion and achieve higher efficiency compared to constant pressure combustion. Figure 5 also shows the mean squared error for all detected ignition times within one cycle for a range of 200 cycles. Convergence was achieved within the first 20 cycles, and the controller maintained this control quality for each set-point change. Even when the system was switched to part load operation, after cycle $k = 50$, the error between the reference and the detected ignition time remained on a similar level. This is a significant result, since it demonstrates that the control system is capable of running the SEC cycle in part load operation with a homogeneous auto-ignition as well as in full load mode.

### 5.3 Part Load Aspects

The results presented above show that the control system can operate the SEC process at different set-points and guarantees a seamless transition between them, even when the load is changed in a drastic, step-wise fashion, which would not be done in a real application. As mentioned, a part load operation should offer a lower energy output at the outlet. A common way to investigate the usable work of the process is to add an expansion over a turbine as shown by Stathopoulos et al. [8]. This is a realistic assumption to analyze the whole combustion process. For the investigation in this work, the absolute values are not as relevant as a general statement about the level of energy emission at the outlet. Therefore, a more basic approach was used. The energy change is described as the difference of enthalpy for an isentropic expansion to atmospheric conditions, cumulated over one cycle. The enthalpy difference is shown in Fig. 7 for two cycles during full load operation as well as for part load operation. It is clearly recognizable that the energy output is lower during part load operation, which is a result of a decreased heat release and consequently lower mean temperatures and pressures. In part load operation, the cumulated enthalpy difference of one cycle is about $10^8$ J smaller than in full load operation.

Part load operation also influences the firing frequency of the combustion tube. The higher amount of cold air that comes with an increased air buffer size leads to a lower mean sonic speed. Therefore, the pressure and suction waves travel at a lower velocity between the inlet and the outlet, slowing down the whole process. If the combustion region is reduced from 40 to 20% of the length of the tube, the firing frequency drops from around 12.5–4.8 Hz. A lower frequency for the decreased combustion region also influences the fuel and air injection times. It is obvious that a larger air buffer requires a longer period of time for air intake, but Fig. 6 shows that the fuel injection duration also rises. This illustrates the deceleration of the process.

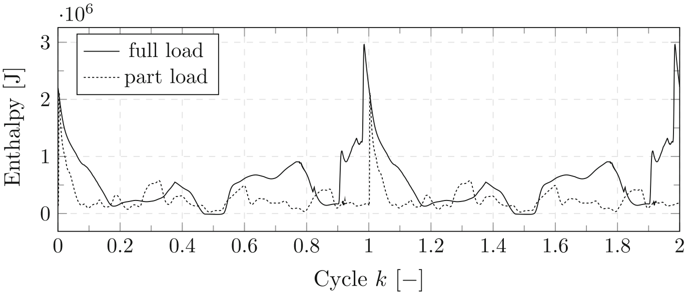

**Fig. 7** Enthalpy difference for two normalized cycles during full load and part load operation. Absolute cycle lengths differ

Consequently, it takes longer to fill 20% of the tube during part load than 40% during full load operation.

Combined with the reduced energy emission, the lower frequency leads to a change in the power of the SEC process. By decreasing the size of the combustion region to 20% of the length of the tube, the power drops from $8.3 \times 10^9$ to $2.9 \times 10^9$ W. These high values are results of the unrealistic tube size mentioned earlier. However, besides the dimension, these values show how well the proposed control system is able to realize a part load operation.

## 6 Conclusion

This work introduced a control system, consisting of three individual controllers, that is capable of maneuvering the SEC process within a certain regime of set-points. By adjusting the size of the combustion region, it is possible to reduce the energy emission at the outlet to realize a part load operation. Furthermore, the frequency can be influenced by changing the combustion region. Homogeneous auto-ignition is marginally influenced by the set-point adjustments, which is an important insight since homogeneous auto-ignition is essential to achieve the thermodynamic benefit of shockless explosion combustion.

This work provides a control architecture that can be used for further theoretical or numerical investigations of the SEC process in general and specifically for the study of the part load operation. To get closer to the real application, it will be necessary to work with more realistic conditions for the compressor as well as the turbine. One solution, as mentioned above, would be the application of a realistic map similar to the work of Stathopoulos et al. [8]. With this expansion model, it will be possible to discuss a part load operation for an overall gas turbine model based on the SEC process in more detail. Finally, more appropriate fuels for an SEC operation have to be included in the simulator.

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## References

1. Bobusch, B., Berndt, P., Paschereit, C.O., Klein, R.: Shockless explosion combustion: an innovative way of efficient constant volume combustion in gas turbines. In: 24th ICDERS, July 28–August 2, 2013, Taiwan (2013)
2. Berndt, P.: Mathematical modeling of the shockless explosion combustion. Ph.D. thesis, Freie Universität Berlin (2016)
3. Rähse, T.S., Stathopoulus, P., Schäpel, J.-S., Arnold, F., King, R.: On the influence of fuel stratification and its control on the efficiency of the shockless explosion combustion. In: Proceedings of ASME Turbo Expo 2018: Turbomachinery Technical Conference and Exposition GT2018, Oslo, Norway, GT2018-76435 (2018)
4. Reichel, T.G., Schäpel, J.-S., Bobusch, B.C., Klein, R., King, R., Paschereit, C.O.: Shockless explosion combustion: experimental investigation of a new approximate constant volume combustion process. J. Eng. Gas Turbines Power **139**(2), 021504 (2016)
5. Burke, M.P., Chaos, M., Ju, Y., Dryer, F.L., Klippenstein, S.J.: Comprehensive $H_2/O_2$ kinetic model for high-pressure combustion. Int. J. Chem. Kinet. **44**(7), 444–474 (2011)
6. Schäpel, J.-S., Wolff, S., Schulz, P., Berndt, P., Klein, R., King, R.: State estimation for reactive Euler equation by Kalman Filtering. CEAS Aeronaut. J. **8**(2), 261–270 (2017)
7. Rähse, T.S., Paschereit, C.O., Stathopoulos, P., Berndt, P., Klein, R.: Gas dynamic simulation of shockless explosion combustion for gas turbine power cycles. In: Proceedings of ASME Turbomachinery Technical Conference and Exposition, Charlotte, USA, GT2017-63439 (2017)
8. Stathopoulos, P., Vinkeloe, J., Paschereit, C.O.: Thermodynamic evaluation of constant volume combustion for gas turbine power cycles. In: Proceedings of the 11th International Gas Turbine Congress, Tokyo, Japan (2015)