Shockless Explosion Combustion

— An Innovative Way of Efficient Constant Volume Combustion in Gas Turbines —

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Abstract

Constant volume combustion (CVC) in gas turbines is a promising way to achieve a step change in the efficiency of such systems. The most widely investigated technique to implement CVC in gas turbine systems is pulsed detonation combustion (PDC). Unfortunately, the PDC is associated with several disadvantages, such as high pressure peaks, entropy generation due to shock waves, and exergy losses due to kinetic energy. This work proposes a new way to implement CVC in a gas turbine combustion system: shockless explosion combustion (SEC). This technique utilizes acoustic waves inside the combustor to fill and purge the combustion tube. The combustion itself is controlled via the ignition delay time of the fuel-air mixture. By adjusting the ignition delay in a way such that the entire fuel-air volume undergoes homogeneous autoignition, no shock waves occur. Accordingly, the losses associated with a detonation wave are not present in the proposed system. Instead a smooth pressure rise is created due to the heat release of the homogeneous combustion. The current paper will explain the SEC process in detail and present the identified challenges. Solutions to these challenges and the numerical and experimental approach are presented subsequently alongside with first preliminary results of the numerical studies.

1 Introduction

The first constant volume combustion gas turbine was invented by Hans Holzwarth [1] in the year 1905. The constant volume combustion in closed vessels created the necessary pressure for the turbine, thus, no compressor was needed.

Better materials, turbine blade cooling, more efficient airfoils in the compressor and turbine, and higher pressure ratios led the way to more and more efficiency in gas turbines. These developments resulted in an efficiency of around 40 % for single cycle application and slightly above 60 % for combined cycle operation including the additional steam cycle.

In recent years, constant volume combustion in gas turbine systems has regained a high interest in the scientific community due to the expected increase in efficiency [2–6]. Heiser and Pratt published a thermodynamic cycle analysis regarding the constant pressure (CPC), constant volume (CVC), and pulsed detonation combustion (PDC) in 2002 [7] for both the ideal and the real cycles. They conclude that the ideal PDC-cycle has a thermal cycle efficiency between 40 % and 80 % depending on the temperature ratio across the compressor.

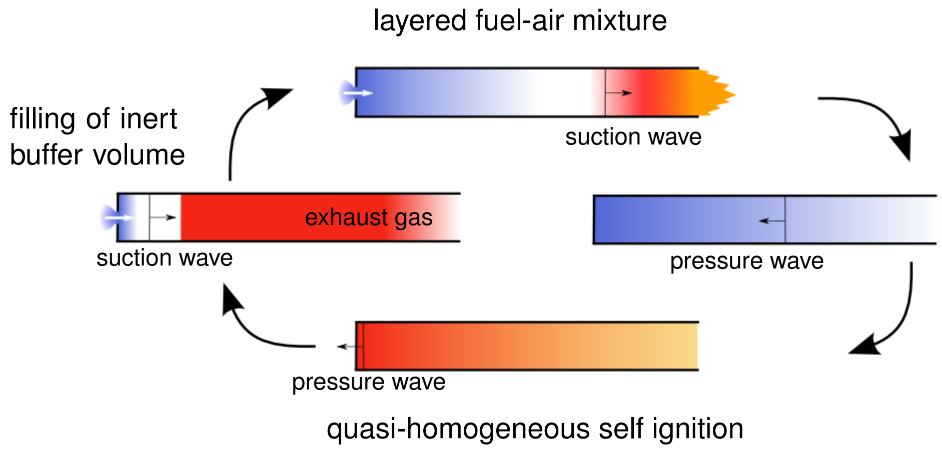

Figure 1: Process cycle of the shockless explosion combustor

This increase in thermal efficiency makes constant volume combustion, in the mentioned study in the form of a PDC, very desirable for the gas turbine community. Unfortunately, this thermodynamic cycle is difficult to achieve from the technical point of view. An overview on the PDC was published in 2004 by Roy et al. [8]. In a pulsed detonation combustor a fast traveling detonation wave is responsible for the combustion of a fuel-air mixture. Due to the very high velocity of the detonation wave (around $2000\,\mathrm{m/s}$ for hydrogen-air flames), the mixture is burnt quasi-instantaneous and the volume of the mixture does not change during the combustion process. However, the detonation wave is also responsible for drawbacks of this combustion system. First of all, the flame front needs space to gain the speed of a detonation wave in the so-called deflagration to detonation transition process (DDT). In this volume the combustion is not fast enough to be considered as constant volume combustion. Secondly, the detonation wave implies a very strong and sharp pressure peak, which is harmful to the turbine and other parts of the engine. Lastly, the detonation wave goes along with a lot of kinetic energy behind itself which might not be fully converted to technical work by the turbine and, thus, is lost.
The proposed shockless explosion combustion process (SEC) uses several physical properties of the fuel air mixture to overcome these drawbacks. The remainder of the paper is organized as follows. The combustion process and the advantages of the SEC process will be described, followed by the numerical approach, as well as the related challenges and some preliminary results.

2 Combustion Process

Like pulsed detonation combustion, the shockless explosion combustion process (SEC) is based on a cyclic combustion process. The main phases of the shockless explosion combustor are shown in figure 1. As denoted in the picture, the SEC cycle is based on four different stages. A standing pressure wave is established inside the combustion tube. The moment when this pressure wave reduces the pressure at the tube inlet below the plenum pressure, the tube is filled with compressor air. After filling a volume with pure air, fuel is added to the combustion air until around $40\,\%$ of the tube is filled with a combustible mixture. The air volume is needed to separate the hot flue gases from the previous cycle and the fresh fuel-air mixture. Due to the hot air from the compressor, the mixture undergoes auto-ignition. The equivalence ratio inside the combustion chamber is adjusted in a way that the ignition delay matches the residence time of the mixture in the tube. Thus, the entire fuel-air volume undergoes homogeneous auto-ignition and the mixture is burnt instantaneously without any shock waves. In addition the ignition delay is adjusted to match the oscillation period. This means that the combustion of the mixture occurs simultaneously with the pressure wave raising the pressure at the tube inlet. The pressure wave is amplified and travels to the end of the combustion tube, where it will be reflected as a suction wave and restart the process. Since this process must be coupled to the acoustic resonance of the combustion tube, the firing frequency will be around $250\,\mathrm{Hz}$ for a tube length of around $80\,\mathrm{cm}$. Besides these values a simple calculation of the process gives an idea of the expected power density of such a combustion tube burning dimethyl ether at a pressure of 30 bar. These parameters are shown in table 1.

length in mm	800	equivalence ratio	1
diameter in mm	40	average temperature in K	1700
filling ratio	0.4	frequency in Hz	258
intermediate air volume ratio	0.05	thermal power in MW	11

Table 1: Approximate operating parameters of one SEC-tube burning dimethyl ether at a pressure level of 30 bar

This process cycle implies several advantages in comparison to pulsed detonation combustion, which are most likely to result in an overall efficiency increase.

1. Smooth pressure rises In contrast to pulsed detonation combustion, no detonation waves are employed in the SEC-cycle, since the SEC only results in a smooth rise of pressure. These smooth pressure changes are less harmful for the machine, allow for a smaller plenum downstream of the combustor, and are not associated with losses.

2. No exergy losses

The detonation wave in a PDC goes along with a significant amount of kinetic energy, which is introduced by the detonation wave. Unfortunately, this kinetic energy is most likely lost in the process since it is difficult to convert this energy to mechanical work in the turbine. In addition parts of the kinetic energy will be dissipated in the plenum downstream of the combustor. The shockless explosion combustor will not imply as much kinetic energy. Thus, the exergy losses associated with the kinetic energy behind the detonation wave are not present in the SEC.

3. No DDT-losses Since a direct ignition of a detonation is extremely energy consuming, pulsed detonation combustors are most likely to employ a deflagration to detonation transition. In order to achieve this transition, at least a small distance is needed which is directly associated to losses because no constant volume combustion is achieved in this region. For the SEC, these losses do not exist due to the homogeneous auto-ignition that does not need any developing distance.

To overcome the challenges of the proposed SEC cycle, the planned experiments are based on and supported by numerical simulations, which will set the sensitivity borders, calculate the needed fuel-air mixtures, and give a more detailed insight into the combustion process. The numerical approach to gain these data is shown in the following section.

3 Simulation

To approximate constant volume combustion within the combustion tube, the chemical reaction must be as homogeneous as possible. The only means of ignition such that the entire volume of gas ignites homogeneously (i.e., not at single hot-spots) is autoignition. Fine grained control over the ignition delay times, despite residual exhaust gases, pressure waves, and other perturbations, is therefore required. Optimization towards this aim poses several challenges and cannot be achieved by experiments alone.

A fast simulation code is needed to be able to perform parametric studies on the process. To this end, a simplified model system has been employed: By only considering radial symmetric flows, the simulation has been reduced to one spacial dimension. The Navier-Stokes equations reduce to the computationally much cheaper Euler equations if viscosity is neglected. This approximation is common

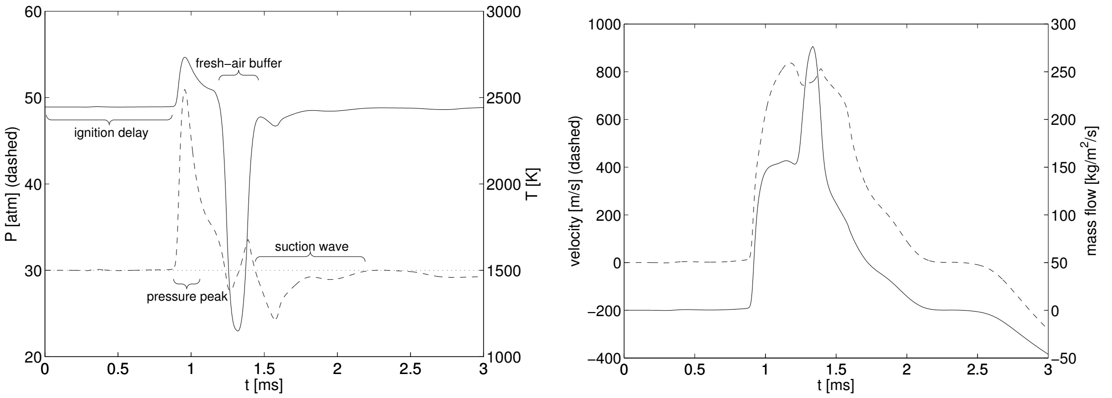

Figure 2: Profiles close to the end of the pipe for a single ignition at machine conditions. Initially filled with $40\,\%$ DME/air at $1000\,\mathrm{K}$ and $30\,\mathrm{atm}$ and zero velocity. This is followed by a $10\,\%$ buffer volume of fresh air at $1000\,\mathrm{K}$. The rest of the tube is filled with burned gas from an earlier cycle. The right end opens into a $30\,\mathrm{atm}$ plenum.

for the simulation of gaseous flows. At a later stage of the project, the full equations will be considered. The equations are closed by the ideal equation of state, $p = \rho RT$. The thermodynamic behavior of each species is modeled using NASA polynomials, i.e., we consider both the gas constant $R = R(Y)$ and the internal energy $e = e(T, Y)$ to depend on the mass fractions Y.

Even with these simplifications, the simulation poses a computational challenge on its own. The reactive Euler equations show distinct multi-scale behavior and are, therefore, numerically stiff. For this reason early investigations are based on heavily under-resolved computations. The knowledge gained will then be used for optimization with more sophisticated models.

The Euler equations are solved using a finite volume approach (FVM) for the gas dynamics and by including an external kinetics solver via strang operator splitting. The HLLE approximate Riemann solver [9] is being used, adopted to the multispecies case by coupling all species' flows to the overall mass flow according to [10]. Second order reconstruction in time and space ensures that the overall simulation is close to second order accurate. The kinetics is handled by a specialized solver compatible with the format used by Flamemaster, a chemical kinetics package by Heinz Pitsch, whose institute will contribute specialized chemical mechanisms to the future work. The ideal gas law is also handled by the kinetics code, which allows for a possible extension to more general equations of state. The species' enthalpies of formation contribute to the internal energy e, coupling mass and energy flow. To avoid problems with this dependence, only the internal energy's difference to a common reference state, i.e., $e = h(T) - h(T_0) - RT$, is stored. The full energy term is then reconstructed within the kinetics solver.

For dimethyl ether, only single ignitions have been simulated to date. In figure 2 the calculated time histories are shown close to the open end of the tube for a typical ignition at machine conditions. More detailed simulations, including optimization towards the SEC case, require long simulation times, but are in progress. Smaller models are expected to arise within the next months. Preliminary calculations with unphysical models of the expected size indicate that they will drastically speed up the simulation process.

4 Challenges

Alongside all of the mentioned advantages, new challenges arise from the shockless explosion combustion concept. The first and most crucial challenge is the correct and reliable conditioning of the mixture. Since the fuel will be injected in the hot compressor air stream, fast and good mixing in the radial plane of the combustor is needed. Otherwise, premature ignition in one or more locations will occur and ignite the entire fuel-air mixture. In addition, the fuel flow must be controlled such that the ignition delay matches the residence time assuring homogeneous autoignition. Finally, the created fuel-air mixture must be separated from the hot walls of the combustion chamber and the hot exhaust gases of the previously cycle by inert air volumes to avoid ignition by the hot environment.

To assess these problems experimentally, a test rig employing water as working fluid was created. Known from literature (e.g., [11, 12]) the mixing of water with dye is a good indicator for the fuel-air mixing in combustion systems. Furthermore, the associated velocities and frequencies are reduced for the same REYNOLDS and STROUHAL numbers due to the different fluid properties of water. To assure homogeneous autoignition of the mixture, the ignition delay time must be precisely adjusted. Challenging for this point is the fact that the ignition delay time depends not only on the equivalence ratio but also on several other parameters, such as temperature, pressure, and fuel composition.

However, from a theoretical perspective, the ideal charge for the model case of a single ignition is obvious: Given a constant flow velocity u and ignition delay times of the fuel mixture as a function $\tau(T, \phi)$, ϕ must be adjusted on injection such that $\tau(T, \phi) = t_{\text{ign}} - t$, which results in the combustor being filled up to ut_{ign} upon ignition. It is practical to keep T constant and only vary ϕ. As mentioned above, additional perturbations must be taken into account for the real SEC process: The whole process is based on acoustic modes oscillating through the tube. The main pressure wave present prior to ignition is a low pressure wave being reflected from the exhaust. If it hits the mixture before ignition, it will change its temperature and, therefore, influence the ignition time, resulting in an inhomogeneous explosion. Solid estimates of the strength and time of such events are needed to achieve accurate predictions. Further potential sources of perturbation are residuals of burnt, hot gas, which might mix with the fuel and heat flux from the walls of the combustor. Their effects are to be evaluated and must also be considered in the control strategy. The aim is to estimate the strength of these effects. At a later stage necessary strategies and sharp estimates will be developed in more detailed simulations.

Another approach is the development of fuels suitable for the SEC-process. Two important parameters of the fuel are the temperature sensitivity of the ignition delay time and the ratio between the ignition delay time and the excitation time, which is the time between ignition and complete combustion.

The lower the temperature sensitivity of the ignition delay, the less precise the temperature needs to be controlled. This will be achieved by making use of the negative temperature coefficient (NTC) behavior of certain fuels. NTC-regions are temperature intervals for which the ignition delay time increases with temperature. By mixing a fuel with pronounced NTC behavior and one without a NTC region, the temperature dependency can be removed within a range of about $200\,\mathrm{K}$, which would potentially suffice to neglect the oncoming waves completely. The risk of detonation waves due to premature ignition can be reduced by using fuels whose excitation time is of similar order as the ignition delay time. When hot spots occur the excitation time determines the propagation speed of the reaction in the mixture. Thus, if the ratio between the ignition delay time and the excitation time is close to unity, autoignition of the surrounding mixture occurs before any detonation cells can develop. The INSTITUT FÜR TECHNISCHE VERBRENNUNG at RWTH AACHEN UNIVERSITY investigates mixtures of fuels to achieve this (see, e.g., [13]).

The second challenge is to achieve the desired firing frequency. To do so, very fast valves are needed to assure the correct filling of the combustion tube. No mechanical valve system that is capable of handling hot flows at such frequencies and, in addition, is reliable over a long operational period is known to the authors. However, fluidic devices seem to be a promising technology to achieve such valve-like behavior without any moving parts. This will guarantee the needed reliability and lower the complexity of the system.

5 Conclusion

The idea of constant volume combustion is promising for a step change in the efficiency of gas turbines. As shown by thermodynamical cycle analysis, the thermal efficiency can be increased to $40\,\%$ – $80\,\%$ for an ideal PDC cycle. Several ideas for the implementation of constant volume combustion in a gas turbine system exist. The most investigated technique is the pulsed detonation combustion that utilizes fast traveling detonation waves to approximate constant volume combustion. These detonation waves are associated with several disadvantages: high pressure peaks, exergy losses due to kinetic energy, and losses due to the shock wave. The proposed shockless explosion combustion overcomes these disadvantages by making use of traveling pressure waves inside the combustion chamber to trigger the process and homogeneous autoignition to create instantaneous combustion without harmful and entropy generating pressure peaks. In addition, the SEC is expected to reach even higher efficiencies than the PDC. Thus, the SEC is very promising for a step change in future gas turbine efficiency.
The main challenges were identified and first solutions were proposed. The work on these challenges from both the experimental and the numerical side are ongoing. In the near future, the technical feasibility of the theoretically predicted behavior will be investigated and assessed. The sensitivity of the process to perturbations in the ideal combustion cycle will be estimated.
More results from the ongoing numerical and experimental investigations will be presented at the conference.

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